ERDC/GSL TR-02-11

US Army Corps
of Engineers®
Engineer Research and
Development Center

Lateral Load Distribution Factors for Military Vehicles on Multi-Girder Bridges

Juan C. Pinero, Mahendra P. Singh,
and James C. Ray

July 2002

Geotechnical and Structures Laboratory

20020805 160

Approved for public release; distribution is unlimited.

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

PRINTED ON RECYCLED PAPER

ERDC/GSL TR-02-11
July 2002

Lateral Load Distribution Factors for Military Vehicles on Multi-Girder Bridges

by Juan C. Pinero, Mahendra P. Singh

Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

James C. Ray

Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Contents

List of Figures iii
List of Tables xii
Preface xv
1—Introduction 1
2—Recent Related Studies 3
3—Objectives 5
4—Methodology 6
5—Military Vehicles Considered 7
6—Types of Bridges 16
7—Analysis of Bridges for Military Vehicles 19
8—Sensitivity of Load Distribution Factors 29
9—Load Distribution Factor Formulas for Military Vehicles 36
10—Comparison of Distribution Factors Calculated by New Formulas and Direct Bridge Analysis 45
11—Proposed Distribution Factors Versus Pre-LRFD and Post-LRFD Distribution Factors 99
12—Conclusions 128
References 129
SF 298

List of Figures

Figure 1. Configuration of HETS vehicle load distribution 8
Figure 2. Configuration of PLS vehicle load distribution 9
Figure 3. Configuration of HEMTT vehicle load distribution 10
Figure 4. Configuration of M113 Tracked vehicle load distribution 11

Figure 5. Configuration of Abrams tracked vehicle load distribution.....12

Figure 6. Configuration of Bradley tracked vehicle load distribution 13

Figure 7. Variation of vehicle position in the transverse direction to obtain maximum moment and shear response.....14

Figure 8. Bending moments and shear forces in different girders calculated by harmonic analysis approach for different vehicle locations in the transverse direction.....15

Figure 9. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average steel girder bridge, single lane loading scenario 22

Figure 10. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average prestressed girder bridge, single lane loading scenario 23

Figure 11. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average concrete T-beam bridge, single lane loading scenario 23

Figure 12. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average steel girder bridge, multiple lane loading scenario 24

Figure 13. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average prestressed girder bridge, multiple lane loading scenario 24

Figure 14. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average concrete T-beam bridge, multiple lane loading scenario 25

Figure 15. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average steel girder bridge, single lane loading scenario.....25

Figure 16. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average prestressed girder bridge, single lane loading scenario 26

Figure 17. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average concrete T-beam bridge, single lane loading scenario.....26

Figure 18. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average steel girder bridge, multiple lane loading scenario.....27

Figure 19. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average prestressed girder bridge, multiple lane loading scenario ...27

Figure 20. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen 1993 formulas, and LDFAC program, average concrete T-beam bridge, multiple lane loading scenario.....28

Figure 21. Sensitivity of bending moment distribution factors steel girder bridges single lane loading scenario 30

Figure 22. Sensitivity of bending moment distribution factors prestressed girder bridges single lane loading scenario.....30

Figure 23. Sensitivity of bending moment distribution factors concrete T-beam bridges single lane loading scenario.....31

Figure 24. Sensitivity of bending moment distribution factors steel girder bridges multiple lane loading scenario 31

Figure 25. Sensitivity of bending moment distribution factors prestressed girder bridges multiple lane loading scenario.....32

Figure 26. Sensitivity of bending moment distribution factors concrete T-beam bridges multiple lane loading scenario.....32

Figure 27. Sensitivity of shear distribution factors steel girder bridges single lane loading scenario.....33

Figure 28. Sensitivity of shear distribution factors prestressed girder bridges single lane loading scenario 33

Figure 29. Sensitivity of shear distribution factors concrete T-beam bridges single lane loading scenario.....34

Figure 30. Sensitivity of shear distribution factors steel girder bridges multiple lane loading scenario.....34

Figure 31. Sensitivity of shear distribution factors prestressed girder bridges multiple lane loading scenario 35

Figure 32. Sensitivity of shear distribution factors concrete T-beam bridges multiple lane loading scenario 35

Figure 33. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, all beam bridges, bending moment in interior girders for single lane 47

Figure 34. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, steel girder, bending moment in interior girders for single lane..... 48

Figure 35. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, prestressed girder, bending moment in interior girders for single lane 49

Figure 36. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, concrete T-beam, bending moment in interior girders for single lane 50

Figure 37. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, all beam bridges, bending moment in interior girders for multiple lane 51

Figure 38. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, steel girder, bending moment in interior girders for multiple lane 52

Figure 39. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, prestressed girder, bending moment in interior girders for multiple lane 53

Figure 40. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, concrete T-beam, bending moment in interior girders for multiple lane 54

Figure 41. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, all beam bridges, bending moment in interior girders for single lane..... 55

Figure 42. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, steel girder, bending moment in interior girders for single lane 56

Figure 43. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, prestressed girder, bending moment in interior girders for single lane.....57

Figure 44. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, concrete T-beam, bending moment in interior girders for single lane.....58

Figure 45. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams Vehicle, all beam bridges, bending moment in interior girders for single lane.....59

Figure 46. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams vehicle, steel girder, bending moment in interior girders for single lane 60

Figure 47. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams vehicle, prestressed girder, bending moment in interior girders for single lane.....61

Figure 48. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams vehicle, concrete T-beam, bending moment in interior girders for single lane.....62

Figure 49. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, all beam bridges, bending moment in interior girders for single lane 63

Figure 50. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, steel girder, bending moment in interior girders for single lane.....64

Figure 51. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, prestressed girder, bending moment in interior girders for single lane 65

Figure 52. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, concrete T-beam, bending moment in interior girders for single lane 66

Figure 53. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in interior girders for single lane 67

Figure 54. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in interior girders for single lane 68

Figure 55. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in interior girders for single lane 69

Figure 56. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in interior girders for single lane 70

Figure 57. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in interior girders for multiple lane..... 71

Figure 58. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in interior girders for multiple lane..... 72

Figure 59. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in interior girders for multiple lane..... 73

Figure 60. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in interior girders for multiple lane..... 74

Figure 61. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in interior girders for single lane..... 75

Figure 62. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in interior girders for single lane 76

Figure 63. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, shear in interior girders for single lane..... 77

Figure 64. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in interior girders for single lane..... 78

Figure 65. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in interior girders for multiple lane 79

Figure 66. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in interior girders for multiple lane..... 80

Figure 67. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, shear in interior girders for multiple lane 81

Figure 68. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in interior girders for multiple lane 82

Figure 69. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in exterior girders for single lane 83

Figure 70. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in exterior girders for single lane 84

Figure 71. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in exterior girders for single lane 85

Figure 72. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in exterior girders for single lane 86

Figure 73. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in exterior girders for multiple lane 87

Figure 74. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in exterior girders for multiple lane 88

Figure 75. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in exterior girders for multiple lane 89

Figure 76. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in exterior girders for multiple lane 90

Figure 77. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in exterior girders for single lane 91

Figure 78. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in exterior girders for single lane 92

Figure 79. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed, shear in exterior girders for single lane 93

Figure 80. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in exterior girders for single lane 94

Figure 81. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in exterior girders for multiple lane 95

Figure 82. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in exterior girders for multiple lane 96

Figure 83. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, shear in exterior girders for multiple lane 97

Figure 84. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in exterior girders for multiple lane 98

Figure 85. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFd and non-LRFD formulas for PLS and HEMTT vehicles, all bridges, bending moment in interior girders for single lane 102

Figure 86. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for HETS vehicle, all bridges, bending moment in interior girders for single lane 103

Figure 87. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for Abrams vehicle, all bridges, bending moment in interior girders for single lane 103

Figure 88. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for M113 and Bradley vehicles, all bridges, bending moment in interior girders for single lane 104

Figure 89. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for all vehicles, all bridges, bending moment in interior girders for single lane 104

Figure 90. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, all beam bridges, bending moment in interior girders for single lane 108

Figure 91. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, steel girder, bending moment in interior girders for single lane 109

Figure 92. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, prestressed girder, bending moment in interior girders for single lane 110

Figure 93. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, concrete T-beam, bending moment in interior girders for single lane....111

Figure 94. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicles, all beam bridges, bending moment in interior girders for single lane....112

Figure 95. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicles, steel girder, bending moment in interior girders for single lane....113

Figure 96. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicle, prestressed girder, bending moment in interior girders for single lane....114

Figure 97. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicle, concrete T-beam, bending moment in interior girders for single lane....115

Figure 98. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, all beam bridges, bending moment in interior girders for single lane....116

Figure 99. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, steel girder, bending moment in interior girders for single lane....117

Figure 100. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, prestressed girder, bending moment in interior girders for single lane....118

Figure 101. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, concrete T-beam, bending moment in interior girders for single lane....119

Figure 102. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, all beam bridges, bending moment in interior girders for single lane....120

Figure 103. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, steel girder, bending moment in interior girders for single lane....121

Figure 104. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, prestressed girder, bending moment in interior girders for single lane....122

Figure 105. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, concrete T-beam, bending moment in interior girders for single lane....123

Figure 106. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for all vehicles, all beam bridges, bending moment in interior girders for single lane....124

Figure 107. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for all vehicles, steel girder, bending moment in interior girders for single lane....125

Figure 108. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for all vehicles, prestressed girder, bending moment in interior girders for single lane....126

Figure 109. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for all vehicles, concrete T-beam, bending moment in interior girders for single lane....127

List of Tables

Table 1. Properties of Typical Steel Girder Bridges in the NMSU Study....17

Table 2. Properties of Typical Prestressed Girder Bridges in the NMSU Study....17

Table 3. Properties of Typical Reinforced Concrete T-beam Bridges in the NMSU Study....18

Table 4. Properties of Existing Bridges considered in this study (Zokai, et al. 1991, 1993)....19

Table 5. Parameter values for the Average Bridges in each category.....29

Table 6. Bending Moment Load Distribution Factor Formulas for Interior Girders PLS and HEMMT Vehicles.....37

Table 7. Bending Moment Load Distribution Factor Formulas for Interior Girders HETS Vehicle.....38

Table 8. Bending Moment Load Distribution Factor Formulas for Interior Girders Abrams Vehicle.....39

Table 9. Bending Moment Load Distribution Factor Formulas for Interior Girders M113 and BRADLEY Vehicles.....40

Table 10. Bending Moment Load Distribution Factor Formulas for Interior Girders All Military Vehicles.....41

Table 11. Shear Load Distribution Factor Formulas for Interior Girders All Military Vehicles.....42

Table 12. Bending Moment Load Distribution Factor Formulas for Exterior Girders All Military Vehicles.....43

Table 13. Shear Load Distribution Factor Formulas for Exterior Girders All Military Vehicles.....44

Table 14. Bending Moment Load Distribution Factor Formulas for Interior Girders Single Lane Loading Scenario.....99

Table 15. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders PLS and HEMMT Vehicles.....100

Table 16. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders HETS Vehicle.....101

Table 17. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders Abrams Vehicle.....101

Table 18. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders M113 and Bradley Vehicles.....101

Table 19. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders All Vehicles.....102

Table 20. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders PLS and HEMMT Vehicles....106

Table 21. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders HETS Vehicle....106

Table 22. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders Abrams Vehicle ...107

Table 23. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders M113 and Bradley Vehicles....107

Table 24. Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders All Vehicles 107

Preface

The research reported herein was sponsored by Headquarters, U.S. Army Corps of Engineers, under Project AT40 Work Package entitled, "Bridge Assessment and Repair." This work was performed primarily by Mr. Juan C. Pinero and Dr. Mahendra P. Singh, Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University. It was accomplished under the direction of Mr. James C. Ray, Geotechnical and Structures Laboratory (GSL), U.S. Army Engineer Research and Development Center (ERDC), under the general supervision of Acting Director, GSL, Dr. David W. Pittman.

At the time of this report, the Director of the ERDC was Dr. James R. Houston, and the Commander and Executive Director was COL John W. Morris III, EN.

The contents of this report are not to be used for advertising, publication or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

1 Introduction

For a load rating analysis of a bridge, one needs to know the maximum bending moment and shear force induced in the beams or girders of the bridge by the vehicular loads. These maximum load effects can be calculated by any of the rigorous analytical procedures such as grillage method, finite element method, finite strip method, or harmonic analysis approach. These rigorous methods are accurate but very cumbersome to use on a day-to-day basis. For a quick estimate of the maximum load effects that include the lateral load distribution characteristics of the deck slab and girder systems, AASHTO (1996) has prescribed simple formulas for lateral load distribution factors for civilian vehicle loads. The distribution factor is used as a multiplier to the bending moment and shear force, calculated for the entire vehicle load applied to the girder as a line load, to obtain the design values of the bending moment and shear force. The distribution factor depends upon the relative stiffness characteristics of the deck-slab and supporting girders, and of course, on the loading pattern of the vehicle on bridge.

The load distribution factors prescribed in the AASHTO Standard Specifications (1996) and AASHTO Guide Specifications for Distribution of Loads for Highway Bridges (1994) were primarily developed for civilian highway traffic (Zokai, Osterkemp, and Imbsen 1991). The vehicle considered for the development of these formulas was an HS-20 truck with only two sets of wheel line loads. However, some military vehicles have more than two sets of wheel line loads, with axle loads different from those of an HS-20 truck. In addition, the load distribution patterns of the tracked military vehicle are quite different from that of an HS-20 truck. These different loading characteristics of military vehicles are likely to cause different distributions of bending moments and shear forces in a bridge than those caused by an HS-20 vehicle. The use of the distribution factors based on the civilian vehicles, as is often done for convenience, could provide an over or under estimation of the load effects (bending moment and shear forces) from military vehicles. If the forces caused by the military vehicles are over estimated, it might unnecessarily restrict the usage of a quite safe bridge by the military vehicles. On the other hand, if the forces are underestimated, then it might also permit the use of a weak bridge by a heavy military vehicle. It is, therefore, desirable to obtain more realistic distribution factors to be applied to military loading to estimate their load effects on the beams and girders of multi-girder bridge systems. Therefore, the work described herein was accomplished to develop simplified lateral load distribution factors for commonly used U.S. military vehicles.

The study considered six different types of military vehicles, three of which were wheeled vehicles and the other three were tracked vehicles. The bridge database used for developing AASHTO distribution factor formulas was also used in this study. The focus of this study was to develop the distribution factor formulas for three different types of bridges: steel girder, prestressed concrete, and concrete T-beam.

The bridges in each category were analyzed for the six types of military vehicles by the harmonic decomposition approach to calculate the distribution factors. The numerically calculated distribution factor values were then processed to generic develop formulas for the distribution factors. The distribution factors formulas are expressed in terms of non dimensional parameters related to girder spacing, girder moment of inertia, bridge span, and deck-slab thickness.

The report provides a total of 52 new formulas for different types of vehicles, different types of bridges, bending moment and shear force values, interior and exterior girders, and for single- and multiple-lane loading cases. The distribution factors calculated with the formulas are compared with those calculated by direct analyses of the bridges to evaluate the accuracy of the proposed formulas. Comparisons are also made between the values calculated by the new formulas, post-LRFD formulas prescribed in 1996 AASHTO Standard Specification, and simple pre-LRFD formulas that were prescribed by AASHTO before 1994.

2 Recent Related Studies

The topic of defining the lateral load distribution factors for highway bridges has been of continued research interest for several decades and, as such, there have been numerous studies in the past. The primary motivation behind all these studies had been to define these factors in as simple a form as is possible to calculate the maximum load effect in the load carrying members of a bridge structure, without carrying out complicated analysis of girder and deck slab system.

Earlier studies on this topic, and the resulting distribution factor formulas, were limited and constrained by the then available analytical and numerical capabilities. Therefore, in the late eighties, the NCHRP sponsored a comprehensive research study by Zokai, Osterkemp, and Imbsen (1991) to develop more accurate, yet simple, formulas to define distribution factors for the design of highway bridges in the United States. This study considered a large data set of 850 bridges from 18 different states in the country. The database included five different types of bridges. The effect of skew angle and that of the continuity of the beams over the supports were also considered. The study primarily considered the "AASHTO HS family" of trucks as the vehicle loads in the analysis. In our opinion, this was the most comprehensive study conducted so far on the lateral load distribution factor analysis. The study led to new and more accurate formulas for calculating the load distribution factors. The formulas were expressed as functions of girder spacing, girder span, girder moment of inertia, slab thickness, and the number loaded lanes. The study also made recommendations about the use of some computer programs for bridge analysis, with the primary focus on the finite element and grillage methods.

Although the above study indicated that the proposed distribution factors were insensitive to different types of vehicle loading patterns, this conclusion was not based on any study with military vehicles, which are very different from the standard civilian trucks. To address the issue of the distribution of load effects by military vehicles, an initial study was sponsored by the Military Traffic Management Command and the Federal Highway Administration Bridge Division. The intent was to evaluate a series of bridges in New Mexico using the New Mexico State Highway and Transportation Department program called OVLOAD. The study examined 539 bridges from the National Bridge Inventory (NBI) for different military vehicle including the HETS (Heavy Equipment Transporter System). It was observed that several bridges in this database were not passable by some loaded military vehicles including HETS. This apparent deficiency of several bridges for military vehicles was attributed to incomplete

consideration of the lateral load distribution of military vehicles by the OVLOAD program. Therefore, this initial study was followed by a more comprehensive study started in October 1998 by New Mexico State University (NMSU).

The purpose of that study was to develop a more accurate computer program to quickly evaluate the passability of the bridges in the NBI database, and to verify the findings with the field test on a few selected bridges. The HETS vehicle was the primary focus of this study, as this particular vehicle was observed to place the most demand on the bridge systems. This NMSU study used a computer code SECAN to calculate the bridge response (bending moments and shear forces), including the lateral load distribution effect, for the HETS loading. This computer code was apparently based the method of harmonic analysis – the method also used by Singh, Thangjithan, and Singh (1998) in the sensitivity study discussed herein. The analytically calculated design force values from the SECAN program were validated by the field tests on selected bridges in Colorado and Texas. This analytical method was then used in program BRGCK, developed to provide capacity rating factors for the bridges in the NBI database to assess their passability for HETS vehicles. The details of this NMSU study are provided in the report by Minor and Woodward (2001).

3 Objectives

The general objective of this study is to develop a simple approach to calculate maximum bending moments and shear forces (load effects) caused by military vehicles in different types of simply supported multi-girder bridge systems. These load effects can be calculated by computer programs that are now available for bridge system analysis. However, the intent is not to use these programs but to use the lateral load distribution factors to provide accurate values of the load effects caused by military vehicles. The main objective of this study is, therefore, to develop simple formulas to provide accurate values of the lateral distribution factors. These lateral load distribution factors can then be used with a simple beam analysis to obtain the maximum load effect in the girders of a bridge system.

The load distribution factor formulas developed in this study are similar to those prescribed in AASHTO Standard Specifications (1996) and AASHTO Guide Specifications (1994). The formulas define the distribution factors as functions of girder spacing, girder span, girder moment of inertia, and slab thickness. They are defined separately for the three types of bridges considered in this study. General formulas that can be used with all bridges are also developed. Formulas both for the bending moment and shear force, in the interior and exterior girders, are provided separately. Specialized formulas are also developed separately for the (1) HETS vehicles, (2) PLS and HEMMT vehicles, (3) Abrams vehicles and, (4) M113 and Bradley vehicles. These easy-to-calculate lateral load distribution factors are intended to provide a quick, convenient, and accurate method for both design and load rating analyses.

4 Methodology

To obtain the distribution factor formulas, first the maximum load effects (bending moments and shear forces) are calculated by a rigorous analytical approach for the six different types of military vehicles placed on three different types of multi-beam slab bridge systems. The analytical approach considers the interaction between the beam girders and the supporting slab, and thus provides accurate values of the maximum load effects including the lateral load distribution. These calculated maximum load effect values are divided by the corresponding maximum values obtained for a simply supported beam loaded with the vehicle load applied as a line load placed directly on the beam. The calculated load distribution factor values are next processed by SAS package to obtain the exponents of the regression equations. The regression equations are expressed in terms of non-dimensional bridge parameters that can also be established by similarity analysis (Douglas 1969). These factors are essentially the same as in the NCHRP study by Zokai, Osterkemp, and Imbsen (1991). Separate "best fit" equations are developed for the different cases of (a) three bridge types (steel beam, reinforced concrete T-beam and prestressed concrete beam bridges), (b) interior and exterior girders, and (c) single lane and multiple lane loading patterns. As mentioned earlier, equations have also been developed separately for four classes of military vehicle considered, as well as a single equation representing all military vehicles.

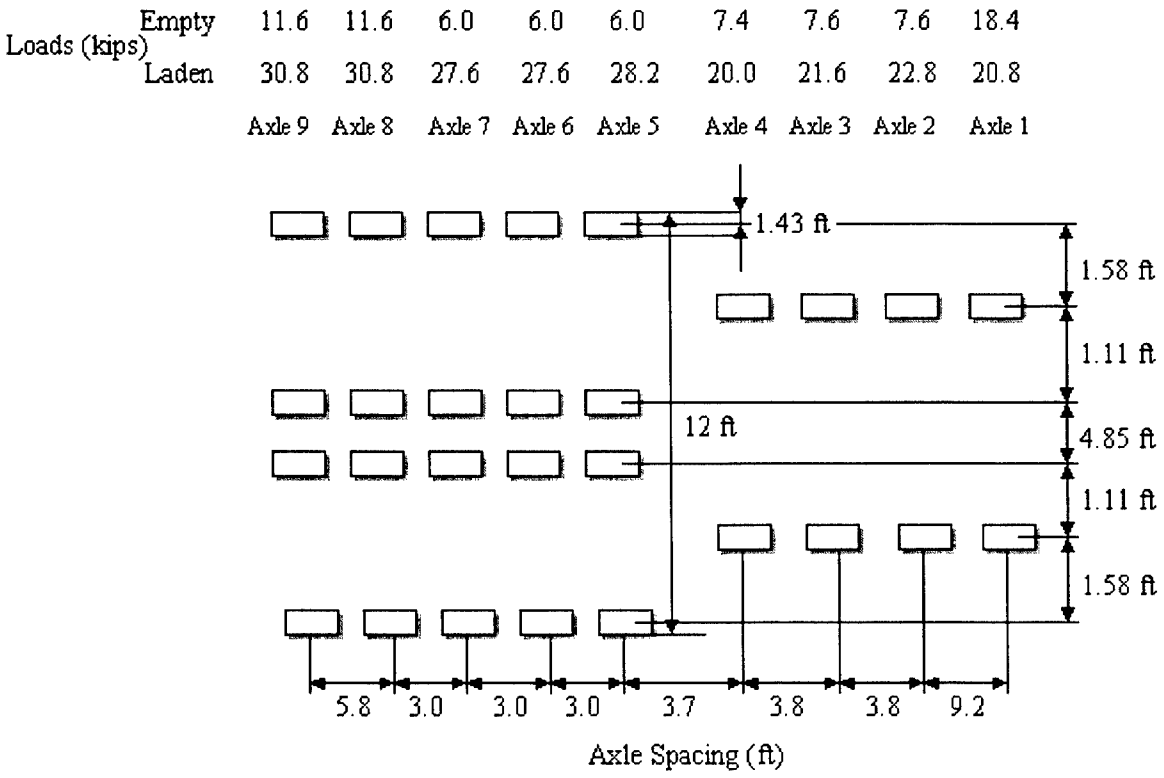
5 Military Vehicles Considered

The study included three wheeled military vehicles: the Heavy Equipment Transporter System (HETS) loaded with the M1A2 Main Battle Tank, the Palletized Load System (PLS) with M1076 trailer at maximum load, and the Heavy Expanded Mobility Tactical Truck (HEMTT) with M1076 trailer at maximum load. Three tracked vehicles were also considered: the M113-A2 Armored Personnel Carrier (M113), the M2 Bradley Infantry Fighting Vehicle (Bradley), and the M1A2 Main Battle Tank (M1). The footprints and axle loads for each of these six vehicles are shown in Figures 1 through 6. It is noted that except for the HETS vehicle, all other vehicles have only two wheel lines of loading. The trailer for the HETS, on the other hand, has six separate wheel lines of loading. The computer program used in the present study considers the actual footprint of the vehicles to obtain the maximum load effect. For this study, the wheel loads were applied as concentrated loads.

The maximum load effects in a girder depend upon the location of the vehicle on the deck. The longitudinal and lateral positions of the vehicles corresponding to the maximum load effect were obtained by varying the position in small increments along and across the bridge. Figure 7 shows the side-by-side locations of the vehicle on the bridge. Figure 8 shows the variations in the bending moments and shear forces in different girders of a typical five-girder steel bridge for different transverse positions of the vehicle on the bridge. For the maximum bending effect in the girders, the position of the vehicle along the bridge was essentially the same as for a simply supported beam loaded with the vehicle load treated as a line load. The maximum bending moment occurred under one of the heavy axles when the axle and the vehicle centroid were equidistant from the two opposite end supports. This longitudinal position for the maximum bending effect was, thus, different for each vehicle considered. The maximum shear forces in the girders were usually obtained when one of the vehicle's heavy axles (usually the last axle) was on or next to the rear end support.

The exterior girders experienced the largest load effects when the centroid of the vehicle was as far as it could go towards the girder from the bridge centerline. This position is usually dictated by the position of the curbs with respect to the position of the exterior girders. Both single lane and multiple-lane-loading patterns were considered. In the multiple-lane loading case, the outside wheel lines of the two adjacent vehicles were kept 4 ft apart.

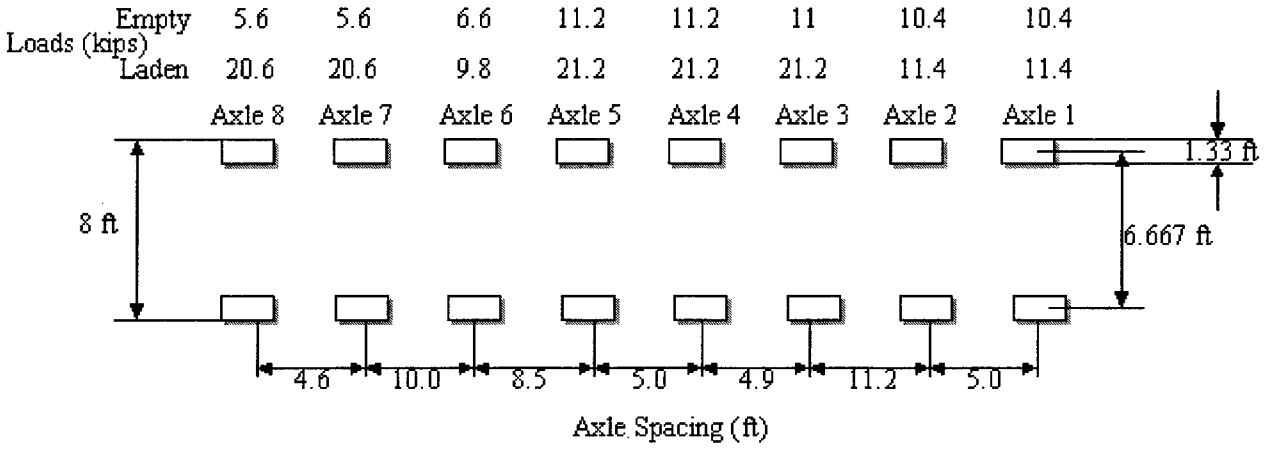
a. Side view



b. Top view

Figure 1. Configuration of HETS vehicle load distribution

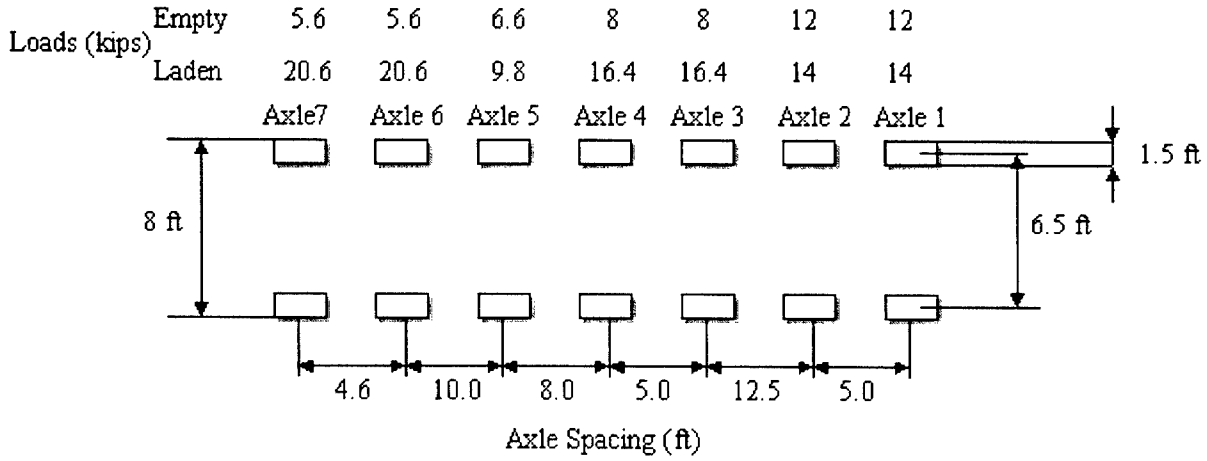
a. Side view



b. Top view

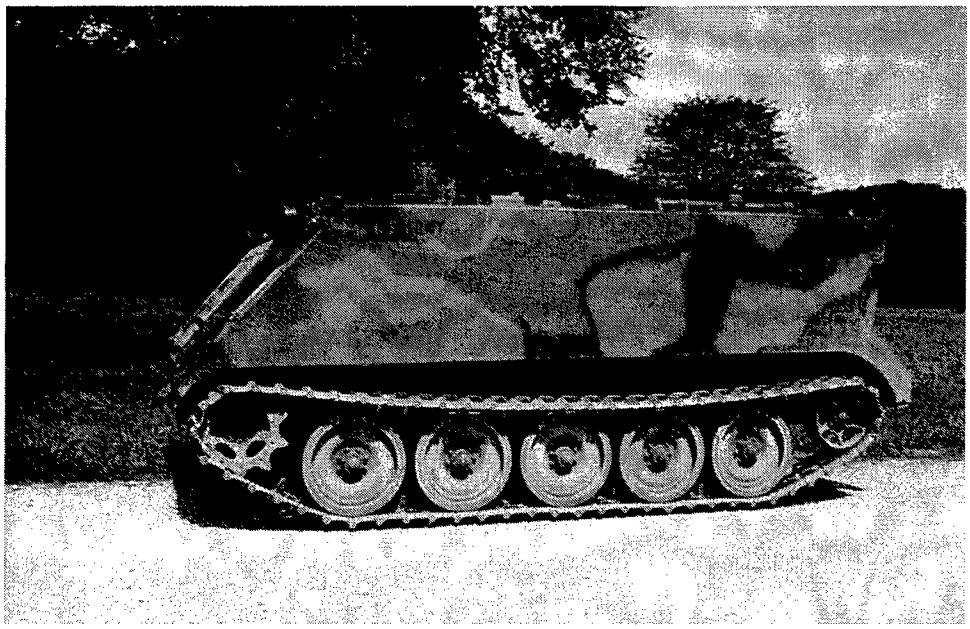
Figure 2. Configuration of PLS vehicle load distribution

a. Side view

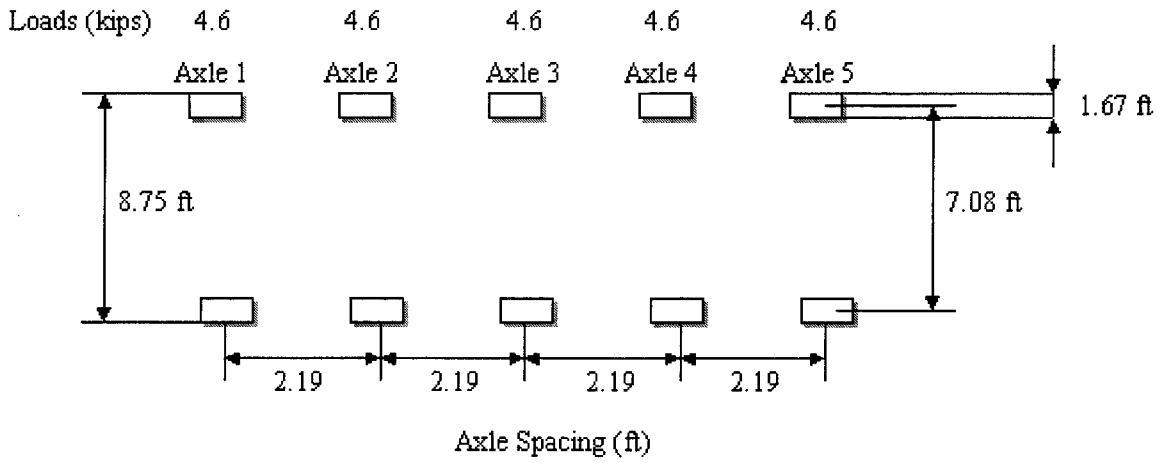


b. Top view

Figure 3. Configuration of HEMTT vehicle load distribution

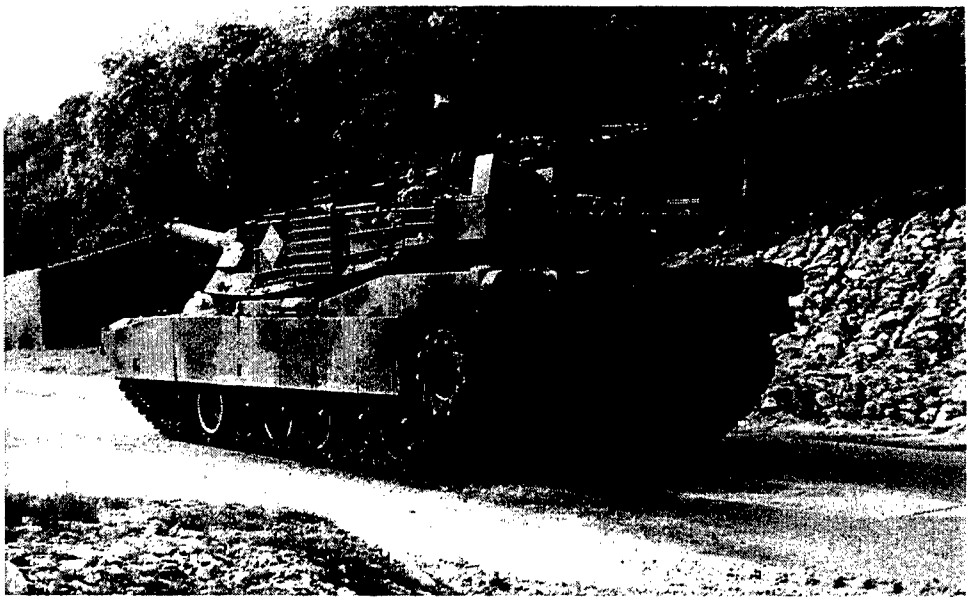


a. Side view

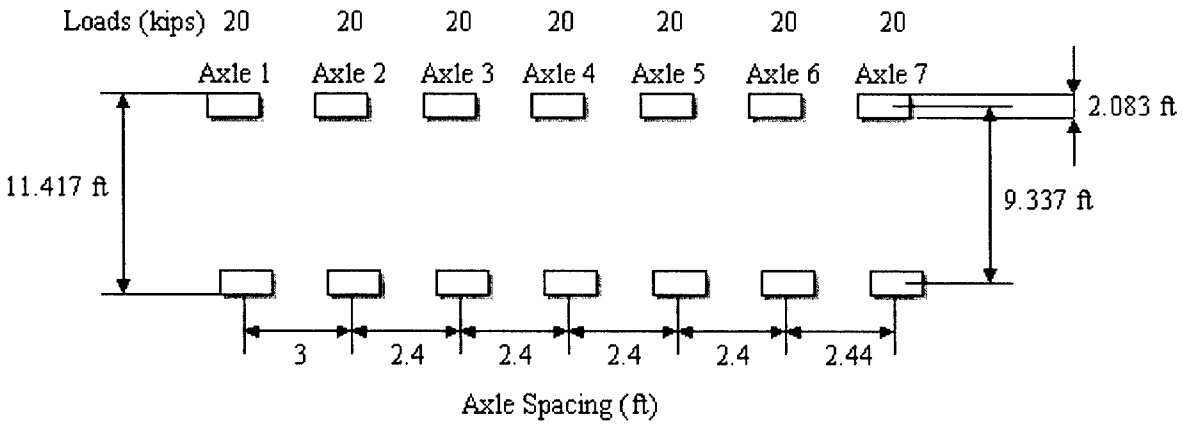


b. Top view

Figure 4. Configuration of M113 Tracked vehicle load distribution



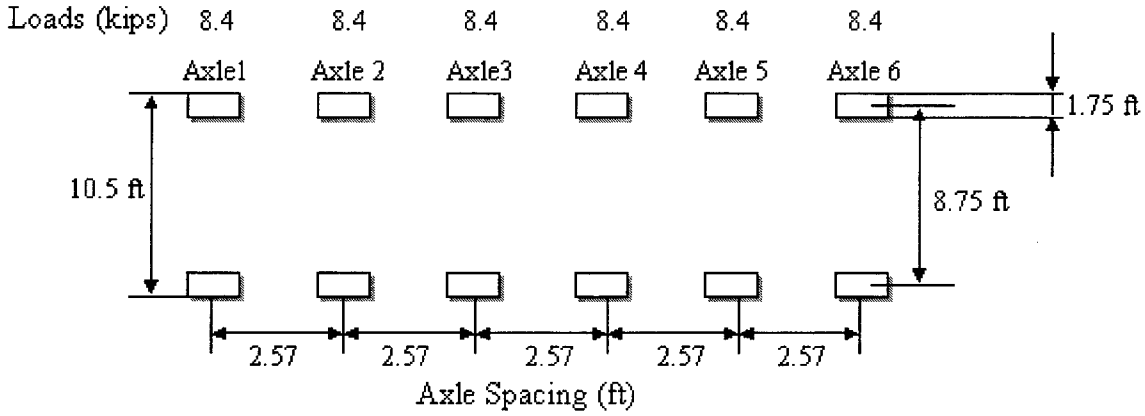
a. Side view



b. Top view

Figure 5. Configuration of Abrams tracked vehicle load distribution

a. Side view



b. Top view

Figure 6. Configuration of Bradley tracked vehicle load distribution

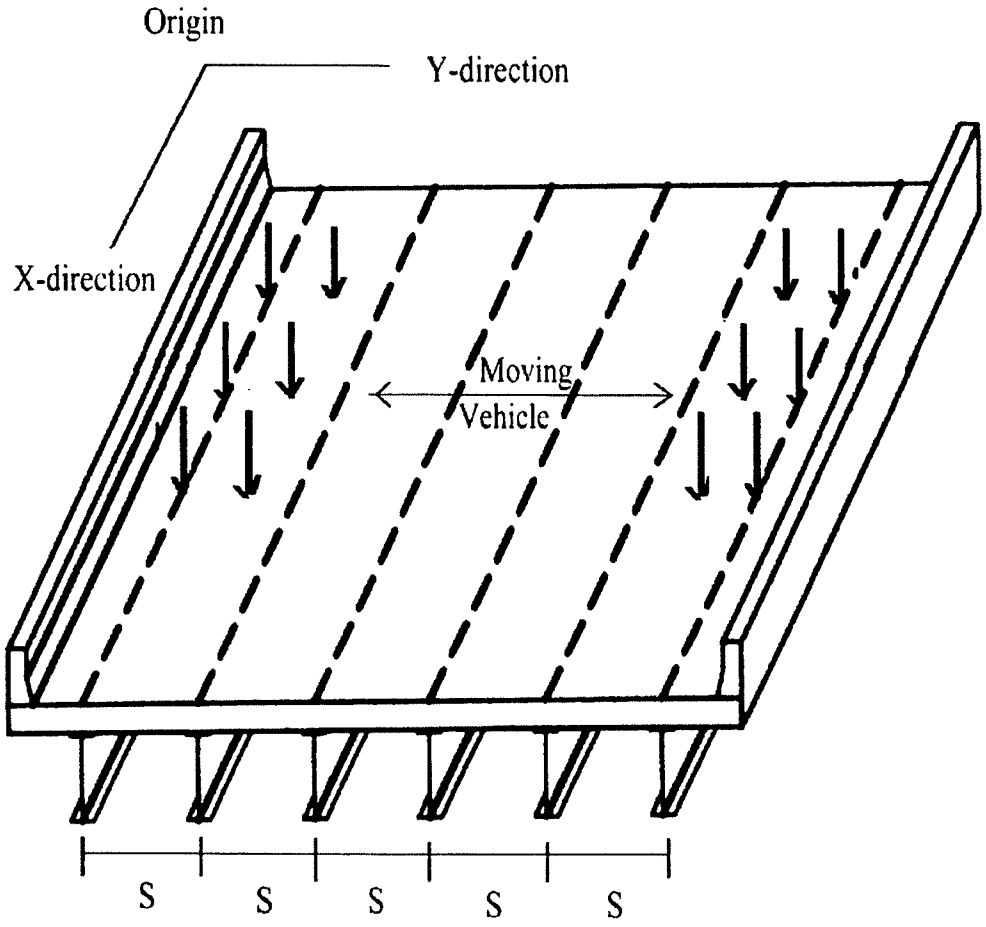
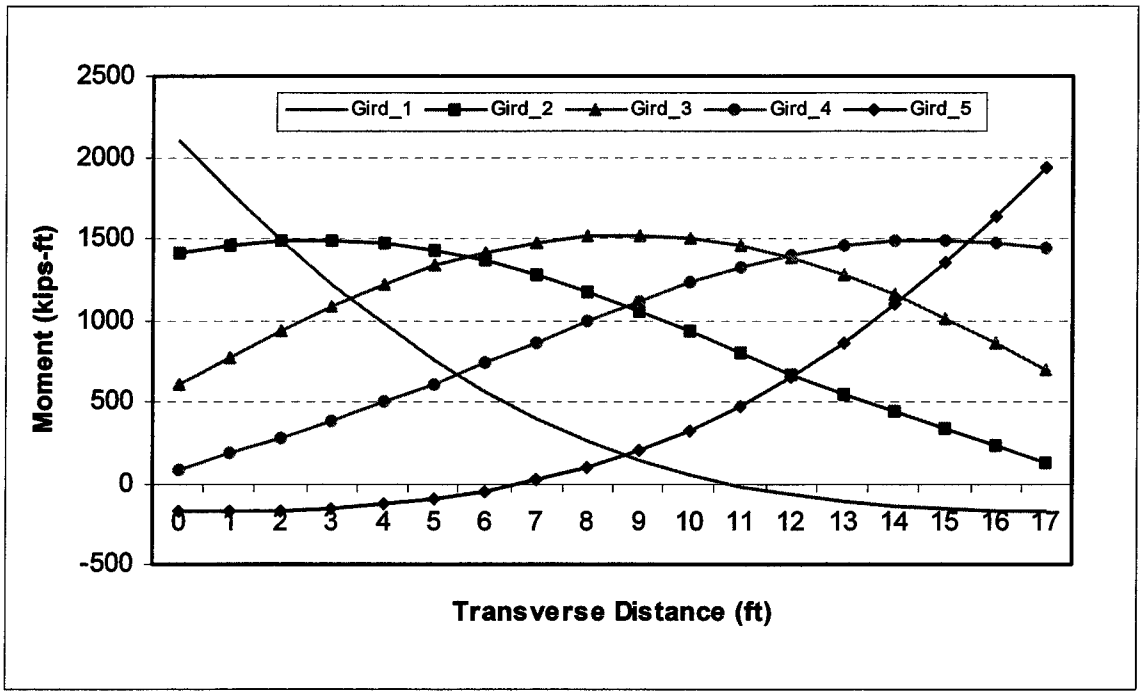
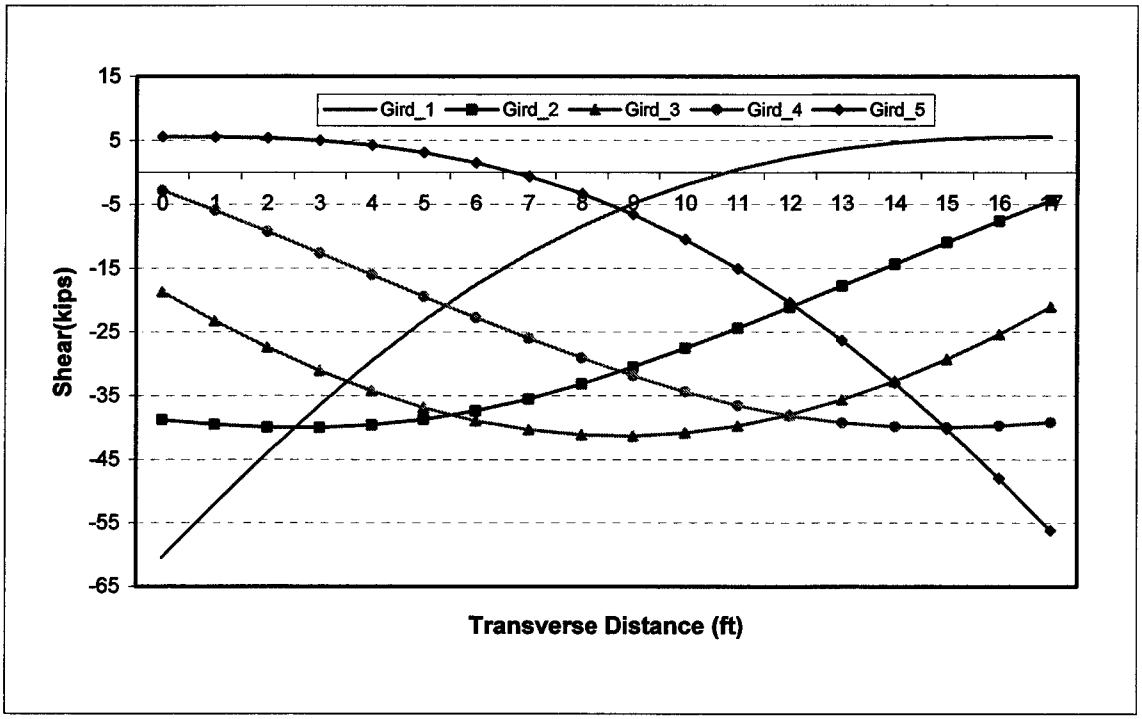


Figure 7. Variation of vehicle position in the transverse direction to obtain maximum moment and shear response



a. Moment Response



b. Shear Response

Figure 8. Bending moments and shear forces in different girders calculated by harmonic analysis approach for different vehicle locations in the transverse direction

6 Types of Bridges

This study focused on the development of lateral distribution factor formulas for the most common multi-girder types of bridges with concrete deck slabs: steel multi-girder bridges, reinforced concrete T-beam bridges, and prestressed concrete I-girder bridges. The study considered the same database of bridges as the one considered by Zokai, Osterkemp, and Imbsen (1991) for the development of distribution factor formulas for the AASHTO. The same database was also used in the NMSU study (Minor and Woodward 2001) for the HETS passability analyses. The Zokai, Osterkemp, and Imbsen(1991) data were analyzed by the NMSU team to define typical parameters for four sets of "typical bridges", which represented the populations of steel multi-girder bridges, reinforced concrete T-beam bridges, prestressed concrete I-girder bridges, and reinforced concrete slab bridges in the database. The parameters for the three typical bridge types considered herein are listed in Tables 1, 2 and 3. The equation shown in Table 1 was obtained by the NMSU team by regression analysis of the Zokai, Osterkemp, and Imbsen (1991) database and is used to define the moments of inertia for the typical set of steel bridges for each set of span and beam spacing values indicated in the table.

Initially, only the typical bridges discussed above were analyzed to develop the distribution factor formulas herein. The distribution factors calculated from these formulas showed a very good fit with those obtained by the direct analysis of these bridges. However, when such a comparison was made with the actual bridges in the Zokai, Osterkemp, and Imbsen (1991) database, the fits were not as good for the steel and prestressed concrete I-girder bridges. This prompted the inclusion of the actual bridges with the typical bridges in the analysis to develop new formulas for the distribution factors for the steel and prestressed concrete I-girder bridges. Inclusion of actual bridges was not required for the T-beam concrete bridges as it did not significantly affect the results. This comparison of the results is discussed in a later section of the report.

Table 1
Moments of Inertia, I (in^4) of Typical Steel Girder Bridges in the NMSU Study

Span, ft	Beam Spacings, ft				
	4	5	6	7	8
50	3,842	4,620	5,556	6,682	8,035
70	5,864	7,052	8,480	10,198	12,264
90	8,950	10,763	12,943	15,565	18,718
110	13,659	16,426	19,754	23,756	28,568
130	20,848	25,071	30,150	36,258	43,603
140	25,756	30,973	37,248	44,793	53,868
# of beams	7	6	5	5	4

Note: Slab thickness varies from 7 to 9 in.

New Mexico University state:

$Ln (I) = 6.4588 + 0.021141 L + 0.184468 S$

Where: I = moment of inertia, $in.^4$)

L= Span length, ft

S= Beam spacing, ft

Table 2a
AASHTO Girder Types of Typical Prestressed Girder Bridges in the NMSU Study

Span, ft	Beam Spacing, ft						
	4	5	6	7	8	9	10
40	II	II	II	II	II	N/A	N/A
50	III	III	III	III	III	N/A	N/A
60	II	II	II	II	II	N/A	N/A
65	III	III	III	III	III	N/A	N/A
70	IV	IV	IV	IV	IV	IV	IV
80	III	III	III	III	III	N/A	N/A
85	IV	IV	IV	IV	IV	IV	IV
100	IV	IV	IV	IV	IV	IV	IV
# of beams	7	6	5	5	4	4	4

Note: Slab thickness varies from 7 to 9 in.

Table 2b
Prestressed Section properties and Moment of Inertia

Type of beam	bu	bb	X1	X2	X3	X4	bw	h	I
	in.	in.	in.	in.	in.	in.	in.	in.	in.^{4}
II	12	18	6	3	6	6	6	36	50,979
III	16	22	7	4.5	7	7.5	7	45	125,390
IV	20	26	8	6	8	9	8	54	260,741

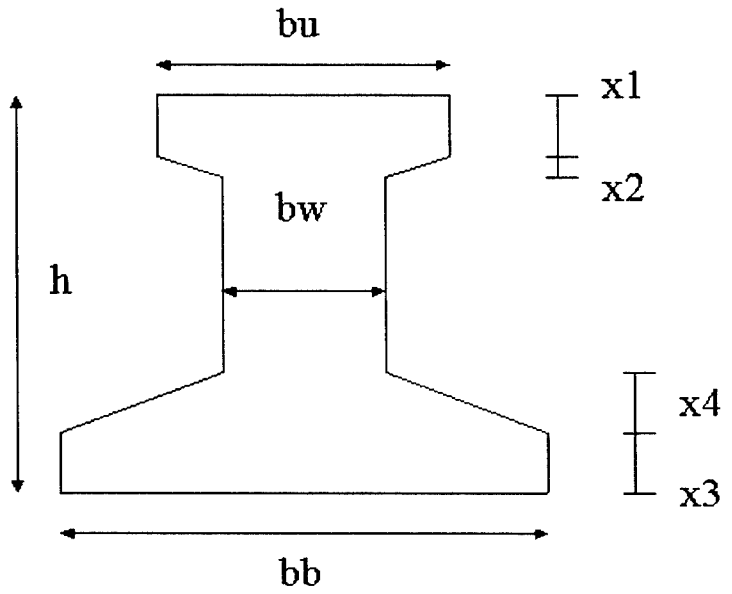


Table 3
Properties of Typical Reinforced Concrete T-beam Bridges in the NMSU Study

Span, ft	Beam Spacing, ft	No. of beams	Stem Width, ft	Icr (in.^{4})
27	9	4	27	49,250
29.2	8.33	4	25	39,390
35	4.75	6	23.75	25,370
42	5.85	5	23.4	40,580
46.8	5.61	6	28.05	40,290
56	9	4	27	141,500
60	4.87	6	24.35	122,900
62.4	5.61	6	28.05	59,590
70	9	4	27	222,130
78	9	4	27	322,500

Note: Slab thickness varies from 7 to 9 in.

Icr = Cracked moments of inertia

7 Analysis of Bridges for Military Vehicles

All typical bridges listed in Tables 1 and 2, along with the existing bridges listed in Table 4, were analyzed for all six military vehicles using the harmonic analysis approach described by Bakt and Jaeger (1989). This harmonic analysis method was re-formulated by Singh, Thangjithan, and Singh (1998) to write a computer program to calculate the maximum load effect for any arbitrary pattern of wheel loads on a simply supported multi-beam slab bridge system

Table 4
Properties of Existing Bridges Considered in this Study (Zokai, Osterkemp, and Imbsen(1991) and Zokai, Mish, and Imbsen (1993)

Seq. No.	Description	Span (ft)	No. Girders	Girder spacing (ft)	Slab thick (in.)	Width(C-C)*, (ft)	Moment of Inertia $in.^4$
1	Arizona-Steel	30	5	7.5	7.75	32	2,364
2	Arizona-Steel	40	5	7.5	7.75	32	2,364
3	California-Steel	113.17	4	8.5	7.13	28	27,833
4	California-Steel	80.66	5	6.25	6	24	9,739
5	California-Steel	130	3	15.5	9.63	39	188,585
6	California-Steel	155	3	15.5	9.63	39	188,585
7	California-Steel	68	4	6.66	6.75	21	14,988
8	California-Steel	116	4	9	7	28	68,862
9	California-Steel	51.25	9	6.5	7	52	5,367
10	California-Steel	51.25	5	6.5	6.5	28	5,367
11	California-Steel	75.25	6	7.75	6.63	37	17,101
12	California-Steel	91.25	6	7.75	6.63	37	24,195
13	California-Steel	151.13	3	12	7.75	28	28,7125
14	California-Steel	75	3	12	7.75	28	215,965
15	Florida-Steel	142	10	9.25	7.5	79.25	59,869
16	Florida-Steel	205	10	9.25	7.5	79.25	75,951
17	Maine-Steel	20	5	5	6.5	22	801

(Continued)

* C-C: curb-to-curb

Table 4 (Continued)

Seq. No.	Description	Span (ft)	No. Girders	Girder spacing (ft)	Slab thick (in.)	Width(C-C)*, (ft)	Moment of Inertia in.^{4}
18	Maine-Steel	50	5	7.92	7.5	30	8,641
19	Maine-Steel	60	5	5	7	22	9,012
20	Maine-Steel	75	5	8.25	6	28	16,856
21	Maine-Steel	90	5	8	9	32	18,554
22	Maine-Steel	110	4	8.5	8.5	28	29,835
23	Maine-Steel	75	5	6	5.75	24	11,048
24	Maine-Steel	20.5	12	2.17	7.5	22	234
25	Maine-Steel	70	6	7.5	8.5	39	7,796
26	Maine-Steel	100	5	7	8	29.83	10,460
27	Minesota-Steel	56.25	7	5.33	7.25	30	5,753
28	Minesota-Steel	28	9	2.58	6.5	19	516
29	Minesota-Steel	43	7	4.83	7	27	3,267
30	Minesota-Steel	51	7	6.25	6.5	30	4,461
31	Minesota-Steel	50	5	7	6	30	6,699
32	Minesota-Steel	68	5	7	6	30	9,012
33	Minesota-Steel	65	5	7	6	30	9,012
34	Minesota-Steel	121.5	8	8.08	9	46.83	41,824
35	Minesota-Steel	98	5	9.83	8.25	36	29,122
36	Minesota-Steel	125	5	9.83	8.25	36	27,508
37	Minesota-Steel	89	4	9.33	6.75	30	10,629
38	New York-Steel	105	6	8.67	12.01	36	15,587
39	New York-Steel	130	6	8.67	12.01	36	19,181
40	New York-Steel	100.73	8	6.6	7	33	43,005
41	New York-Steel	87.3	5	7	8.5	28	17,871
42	Ohio-Steel	39	5	5.75	6.75	24	3,267
43	Ohio-Steel	43	4	7.5	8	28	3,989
44	Ohio-Steel	42.5	12	3.21	4.42	36	2,096
45	Ohio-Steel	27	5	5.75	7.25	24	1,327
46	Ohio-Steel	65.54	5	5.75	7.25	24	6,699
47	Ohio-Steel	74.5	7	8.33	8.5	50	14,988
48	Ohio-Steel	66.25	7	8.33	8.5	50	9,739
49	Ohio-Steel	80	7	8.33	8.5	50	12,103
50	Ohio-Steel	93.12	7	8.33	8.5	50	16,092
51	Ohio-Steel	56	7	8.33	8.5	50	9,739
52	Oklahoma-Steel	36	5	5.25	8.75	20	3,000
53	Oklahoma-Steel	34.75	5	5.25	8.75	20	3,000
54	Oklahoma-Steel	50	5	5.17	6.5	22	6,699
55	Oklahoma-Steel	30	6	4.5	6	24	1,327
56	Oklahoma-Steel	61	6	4.92	7.5	24	7,442

(Continued)

* C-C: curb-to-curb

Table 4 (Concluded)

Seq. No.	Description	Span (ft)	No. Girders	Girder spacing (ft)	Slab thick (in.)	Width(C-C)*, (ft)	Moment of Inertia in.^{4}
57	Oklahoma-Steel	41.25	5	6.58	7.5	28	6,699
58	Oklahoma-Steel	59.83	5	6.58	7.5	28	10,470
59	Oklahoma-Steel	37.17	5	5.25	8.75	20	2.364
60	Oklahoma-Steel	38.75	5	6.58	7.5	28	4,461
61	Oklahoma-Steel	38.75	5	5.25	8.75	20	2,364
62	Oklahoma-Steel	125	4	11	10	38	51,463
63	Oklahoma-Steel	160	4	11	10	38	51,463
64	Oregon-Steel	140	6	13.5	6.5	58	203,546
65	Oregon-Steel	113	6	9	7	70	27,429
66	Oregon-Steel	142	6	9	7	70	27,429
67	California-Prestressed	113	7	6.42	6.87	40	318,000
68	California-Prestressed	96	8	7.5	6.25	52	248,000
69	California-Prestressed	70.5	8	7.5	6.25	52	248,000
70	California-Prestressed	84	10	7	6.25	66	187,800
71	California-Prestressed	61.63	10	7.66	6.25	73	63,300
72	California-Prestressed	27	10	7.66	6.25	73	63,300
73	California-Prestressed	84	19	9.1	7.13	188	187,800
74	California-Prestressed	67.5	7	6.83	6	32	137,300
75	Florida-Prestressed	40	4	9.7	7	28	50,980
76	Florida-Prestressed	60	6	5.83	7	28	50,980
77	Florida-Prestressed	82	5	9.69	7.5	44	260,730
78	Florida-Prestressed	32.5	4	6.75	7	26	125,390
79	Florida-Prestressed	72	4	6.75	7	26	125,390

* C-C: curb-to-curb

To verify the numerical accuracy of the program used herein, distribution factors for the AASHTO HS-20 standard truck were calculated and compared with the results obtained from the equations by Zokai, Osterkemp, and Imbsen (1991) and those obtained by the computer program LDFAC (Zokai, Mish, and Imbsen., 1993). This later program has been recommended by Zokai, Mish, and Imbsen (1993) for level two type of analysis of highway bridge systems and is based on the grillage method of analysis. It represents a multi-girder and deck system by a grillage consisting of interconnected beam elements. It is important that the equivalent bending and torsional stiffness properties of these beam elements are properly chosen to represent the girders and deck of a bridge. The wheel loads also must be transferred properly to the nodes of the interconnecting nodes of the grillage.

The comparison of the distribution factor results is made in Figures 9 through 20. The first six figures are for the bending moment distribution factors and the next six for the shear force distribution factors. Both single lane and multiple-lane-loading scenarios are included. As can be seen, the bending moment distribution factors calculated by different methods are reasonably close to each other, with some being closer than others. There is a somewhat larger difference

in the shear force results, especially for the multiple-lane-loading pattern. In general, the differences in the results obtained by the two computer programs (harmonic analysis and LDFAC) are not overly surprising as they use quite different analytical formulations. The LDFAC results, based on the grillage approach, would be considered to produce less accurate results because of the representation of the bridge continuum by discrete interconnected beam elements. The small differences between the results obtained by the Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas and those obtained by harmonic analysis can also be justified, as the Zokai formulas were developed to represent a wide range of bridge types and parameters.

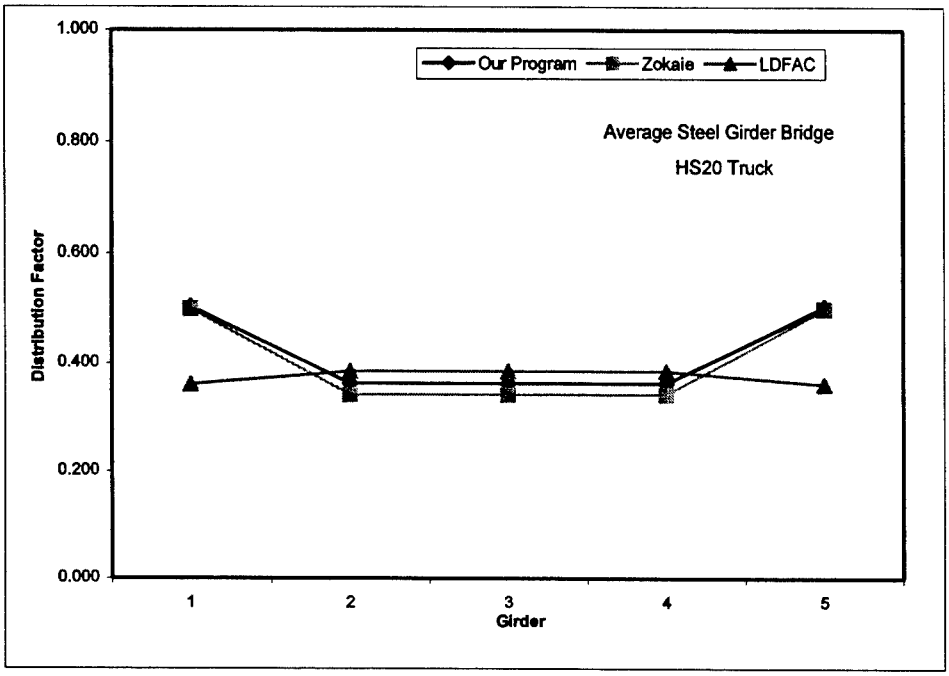


Figure 9. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average steel girder bridge, single lane loading scenario

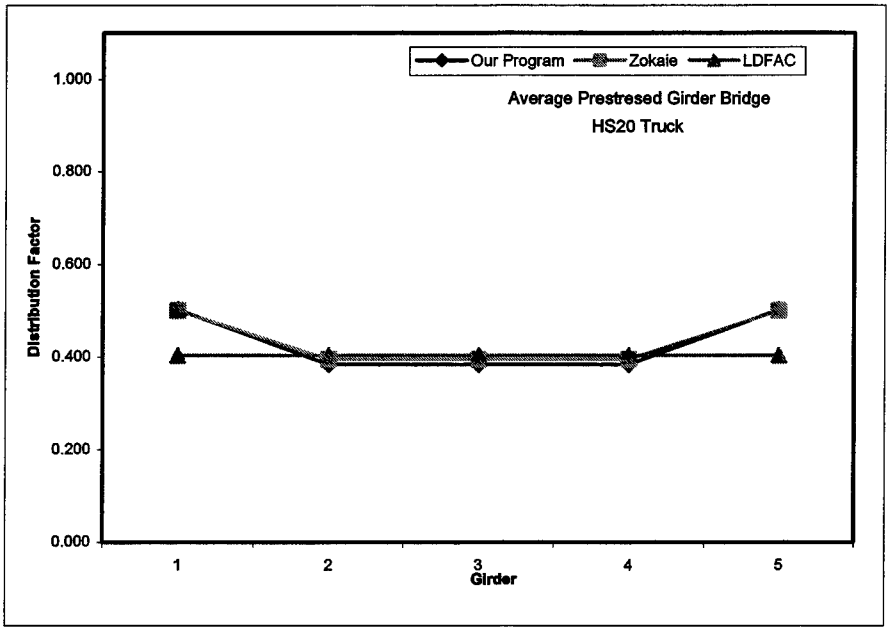


Figure 10. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average prestressed girder bridge, single lane loading scenario

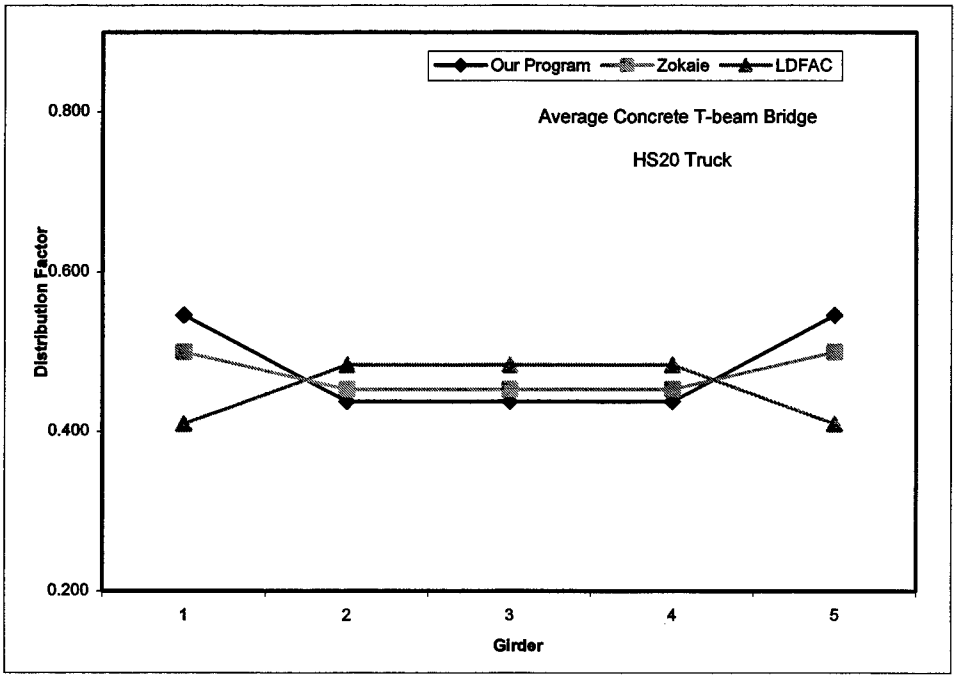


Figure 11. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average concrete T-beam bridge, single lane loading scenario

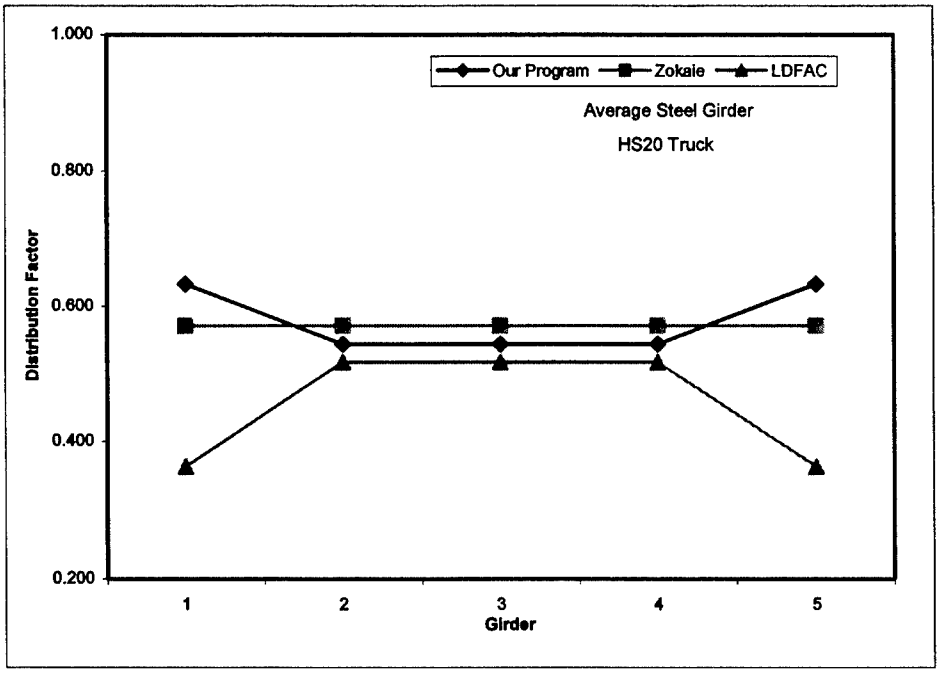


Figure 12. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average steel girder bridge, multiple lane loading scenario

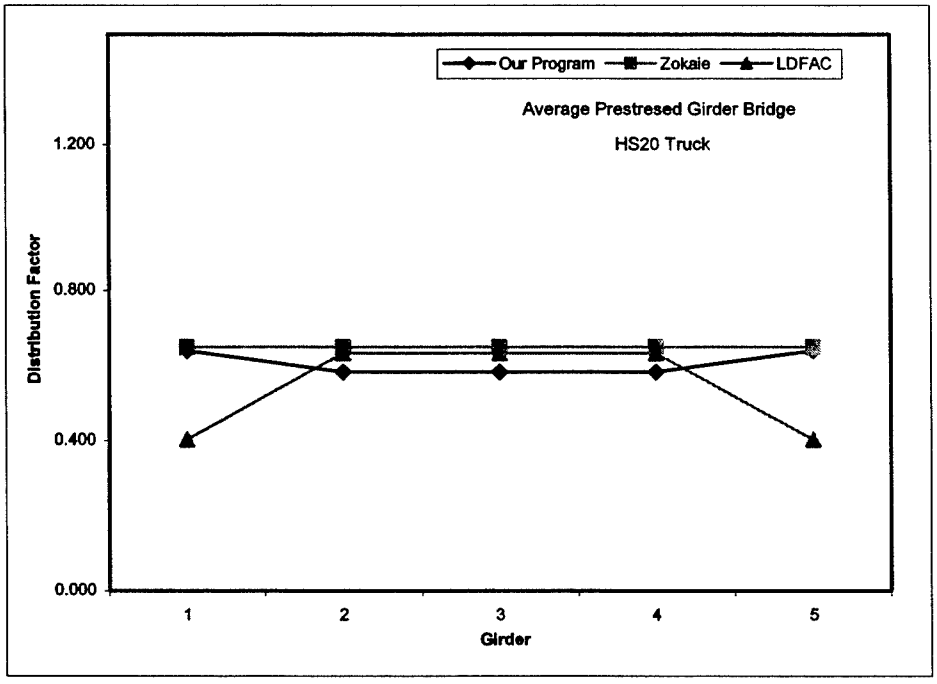


Figure 13. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average prestressed girder bridge, multiple lane loading scenario

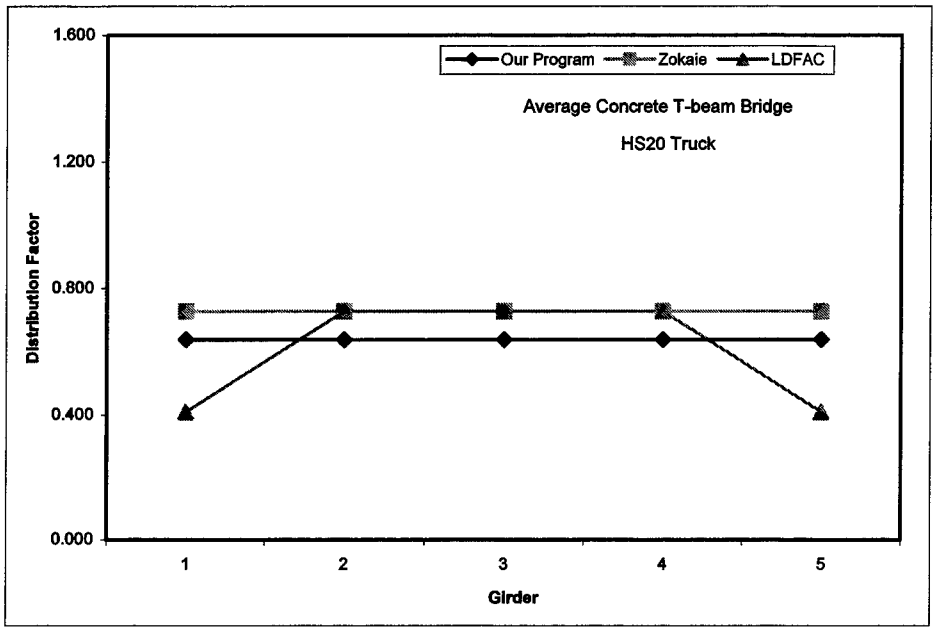


Figure 14. Comparison of bending moment distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average concrete T-beam bridge, multiple lane loading scenario

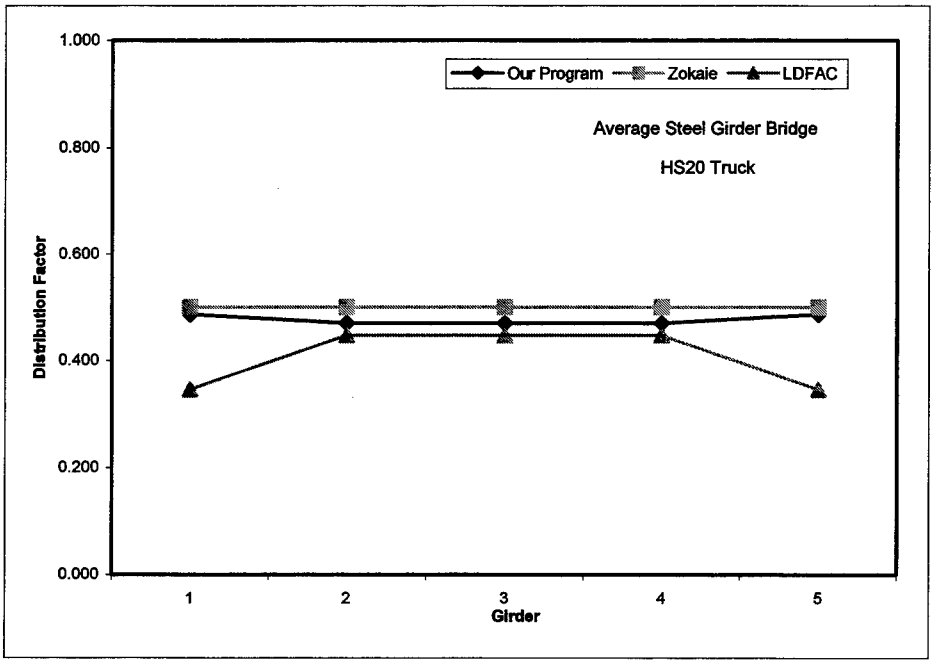


Figure 15. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average steel girder bridge, single lane loading scenario

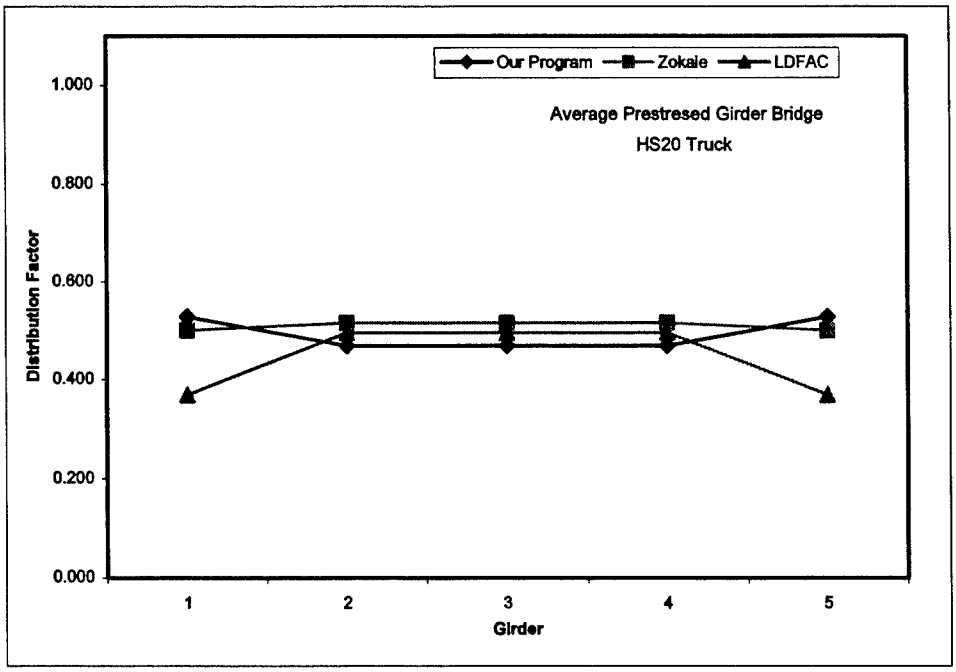


Figure 16. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average prestressed girder bridge, single lane loading scenario

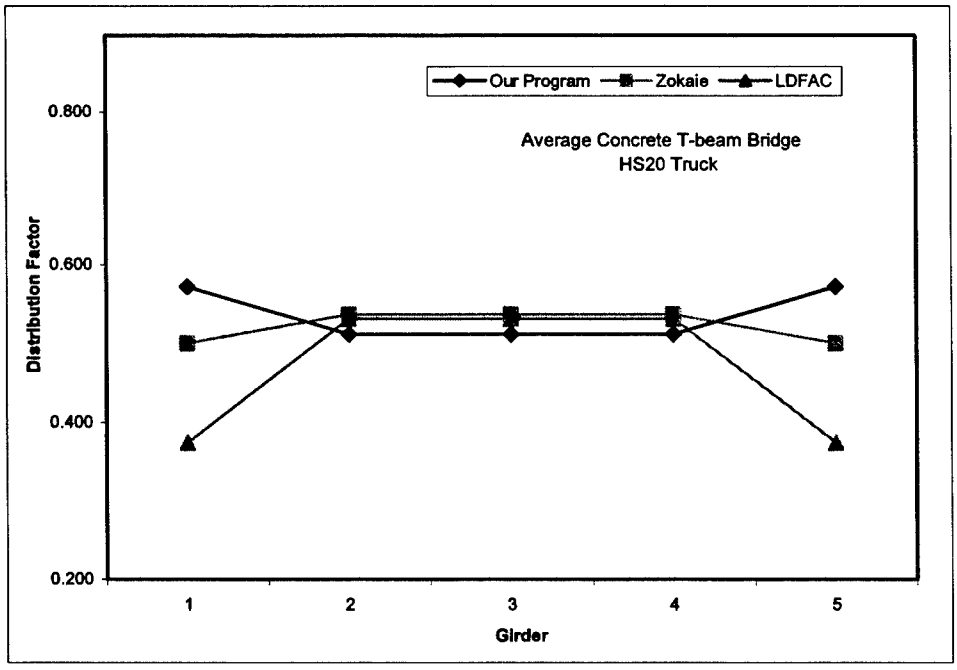


Figure 17. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average concrete T-beam bridge, single lane loading scenario

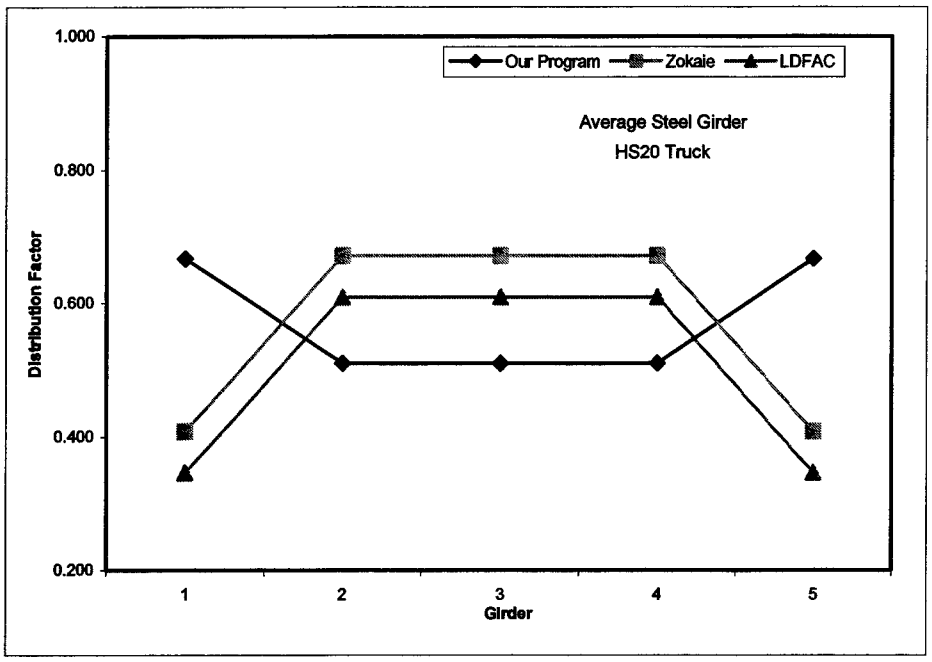


Figure 18. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average steel girder bridge, multiple lane loading scenario

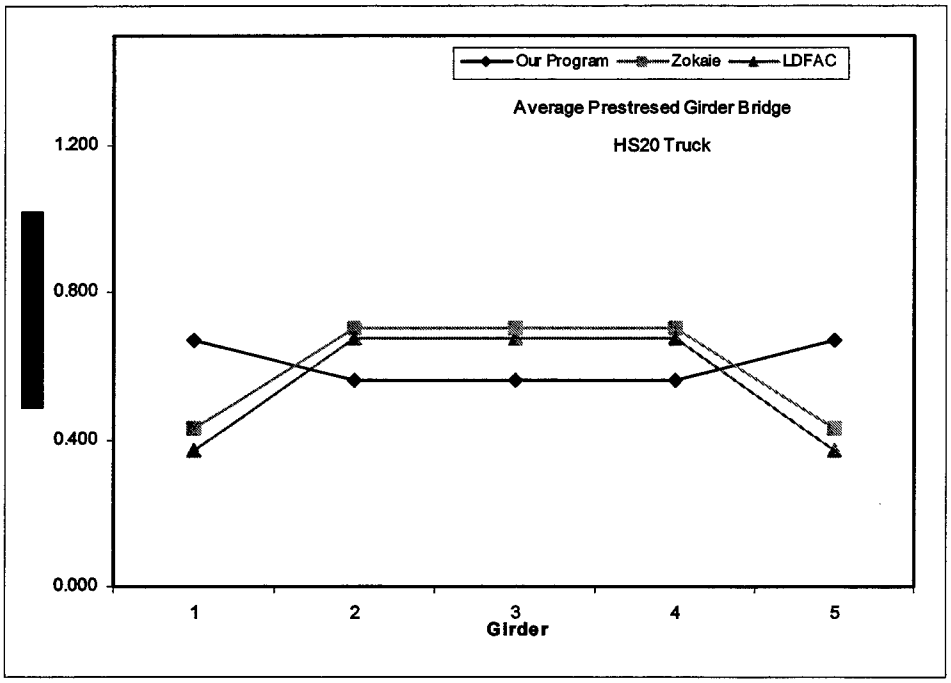


Figure 19. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average prestressed girder bridge, multiple lane loading scenario

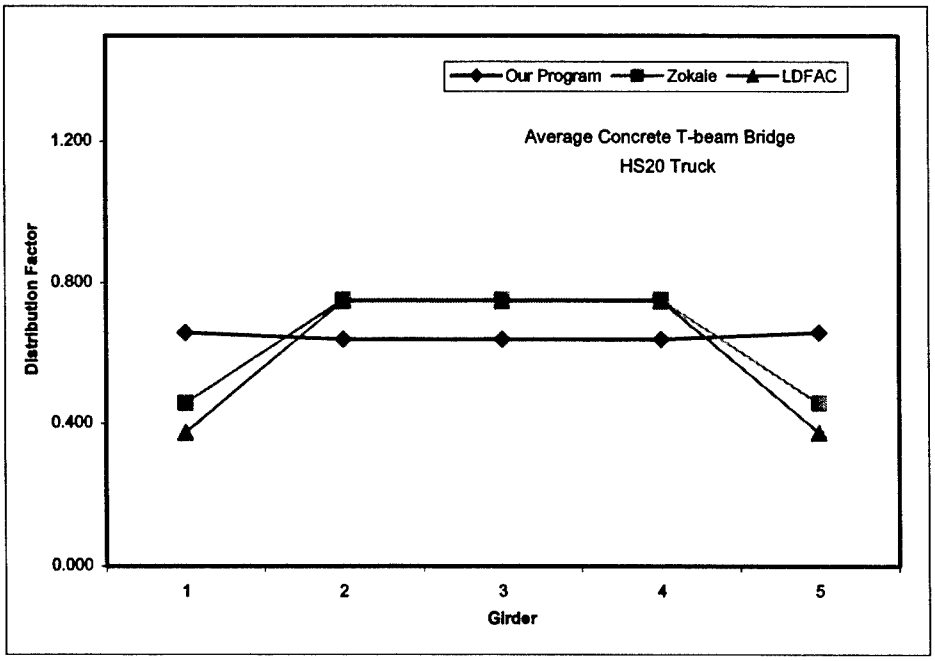


Figure 20. Comparison of shear distribution factors calculated by harmonic analysis approach, Zokai, Osterkemp, and Imbsen (1991) and Zokai, Mish, and Imbsen (1993) formulas, and LDFAC program, average concrete T-beam bridge, multiple lane loading scenario

8 Sensitivity of Load Distribution Factors

It is of interest to examine the sensitivity of the load distribution factors with respect to bridge parameters that effect them. This helps to identify the parameters that are most important and thus ought to be given special consideration in their numerical measurements. The bridge parameters considered are the span, girder spacing, slab thickness, and girder moment of inertia. Numerical results for sensitivity analysis were obtained for the average bridges in the three bridge categories. The properties of the three average bridges are shown in Table 5. Figures 21 through 32 show the sensitivity results for these bridges. The first six figures (Figures 21 through 26) are for the bending moment distribution factors and the next six figures (Figures 27 through 32) are for the shear force distribution factors. Both, the single lane and multiple lane loading scenarios are considered. The figures show the distribution factor values plotted against the normalized parameter value. (The parameter value is normalized by dividing it with the average value of the parameter.) It is noted that the girder spacing is the most important parameter. The second most important parameter is the bridge span, especially for the short span bridges. The parameters of slab thickness and girder moment of inertia do not seem to be as important as the other two parameters, except for the shear force factor in the T-beam bridges (see Figures 29 and 32).

Table 5
Parameter values for the Average Bridges in each category

Type of Bridge	No. of Girders	Girder Spacing, ft	Span, ft	Inertia, in.^{4}	Width, ft	Slab thick, in.
Steel	5	6.00	98.33	19,675	25.0	8.00
Prestressed	5	6.46	70.87	17,1004	25.5	8.00
T-beam	5	7.10	50.64	106,350	26.1	8.00

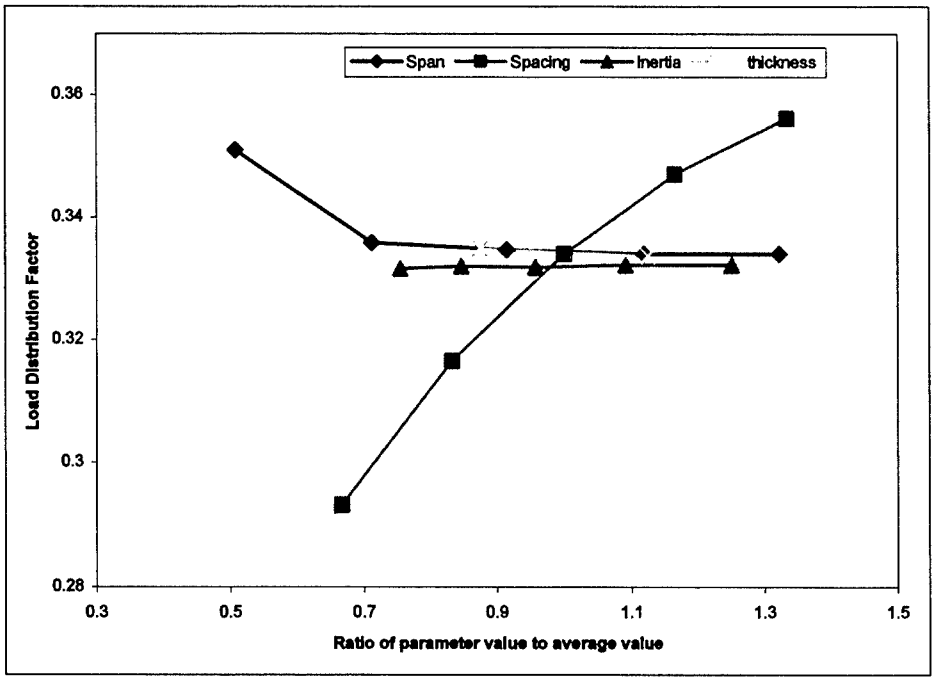


Figure 21. Sensitivity of bending moment distribution factors; steel girder bridges; single lane loading scenario

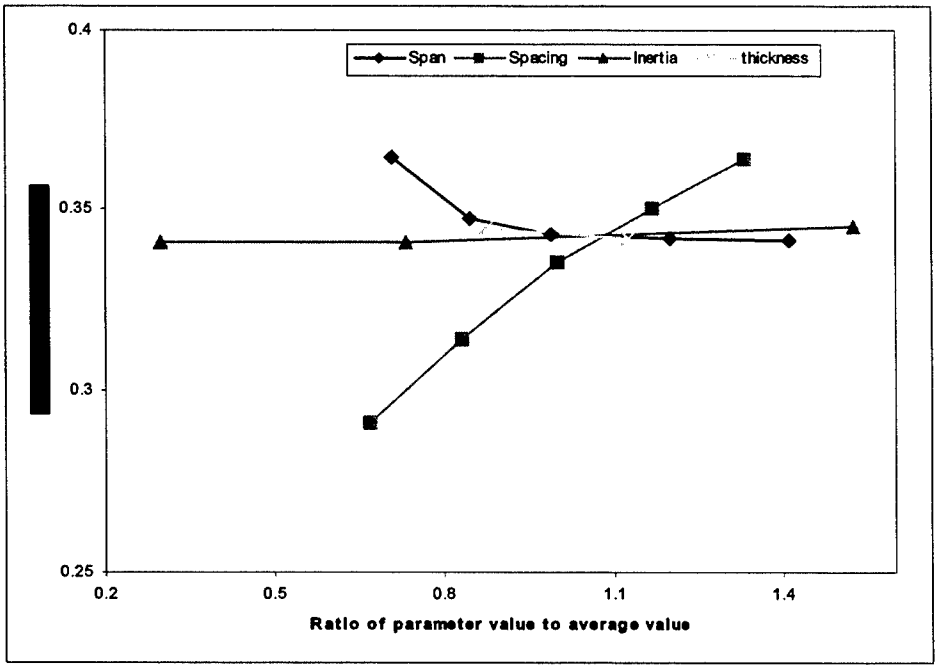


Figure 22. Sensitivity of bending moment distribution factors; prestressed girder bridges; single lane loading scenario

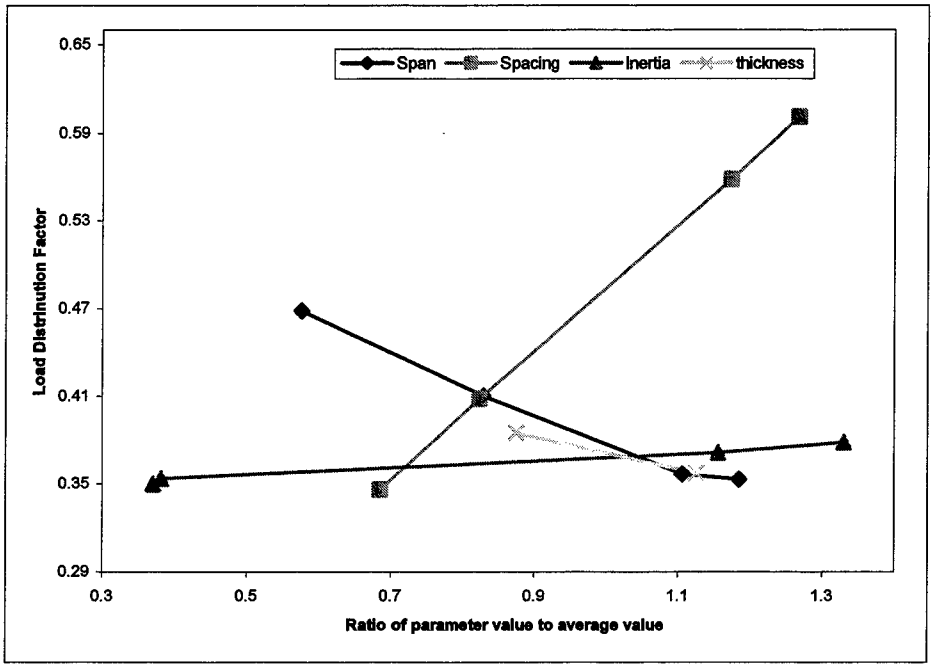


Figure 23. Sensitivity of bending moment distribution factors; concrete T-beam bridges; single lane loading scenario

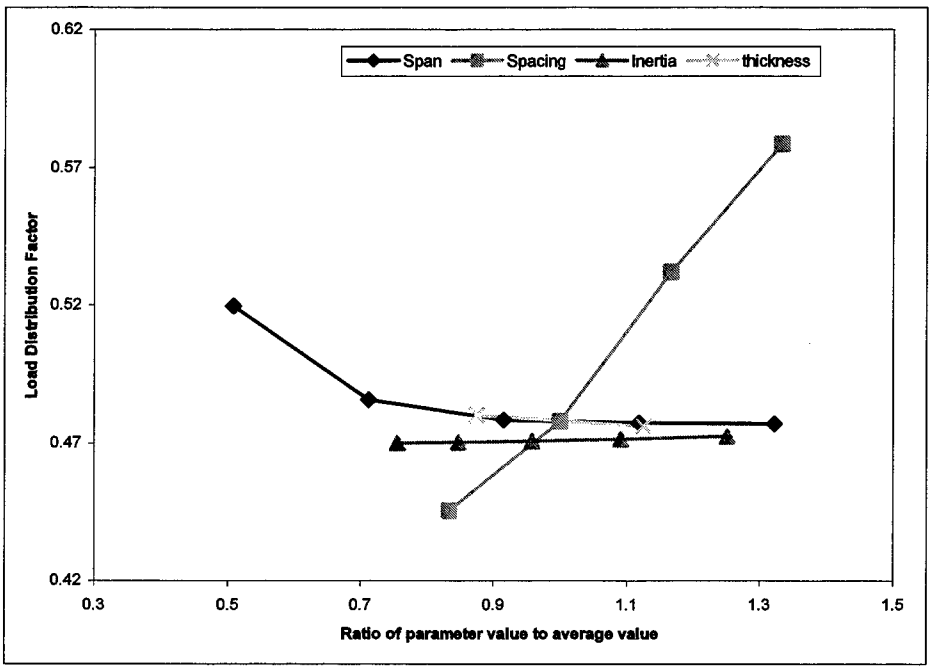


Figure 24. Sensitivity of bending moment distribution factors; steel girder bridges; multiple lane loading scenario

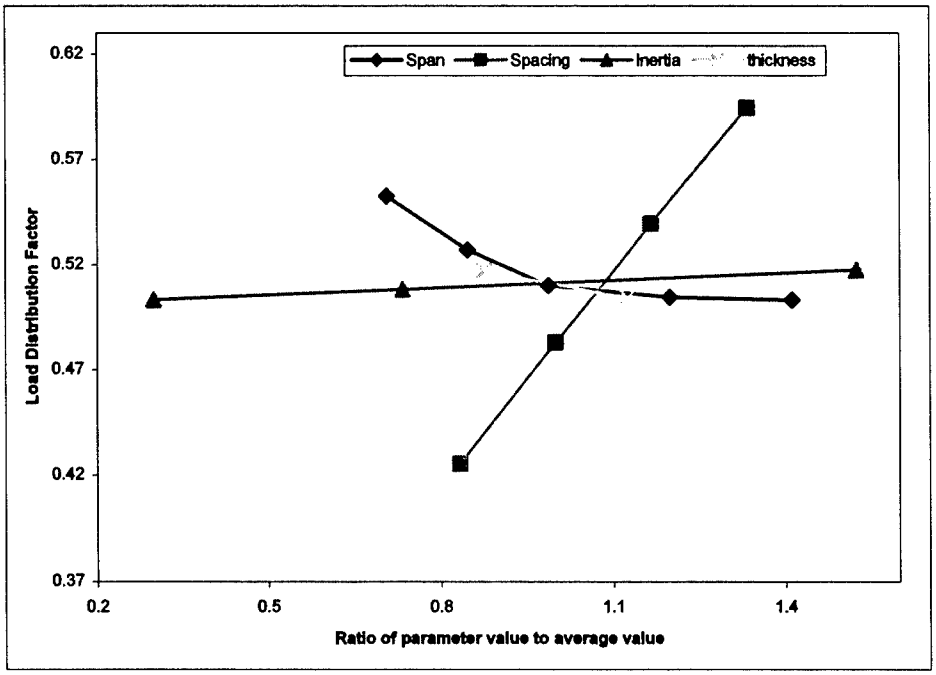


Figure 25. Sensitivity of bending moment distribution factors; prestressed girder bridges; multiple lane loading scenario

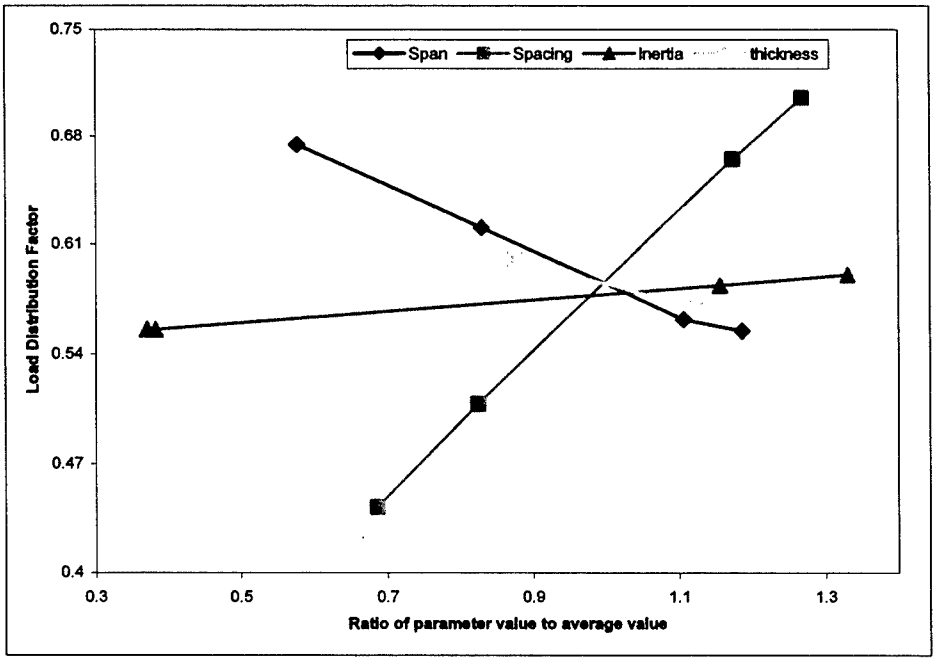


Figure 26. Sensitivity of bending moment distribution factors; concrete T-beam bridges; multiple lane loading scenario

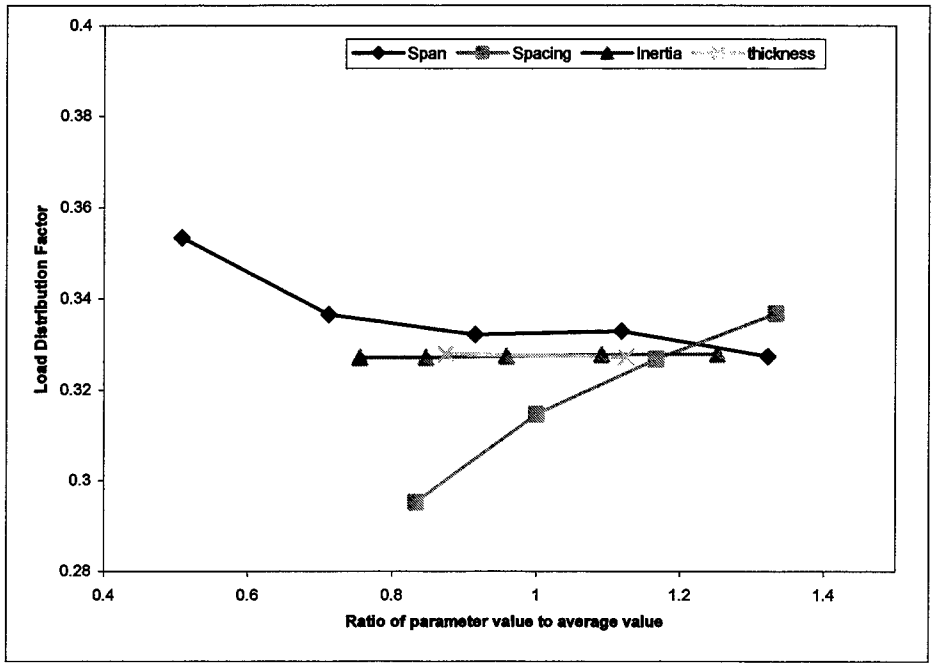


Figure 27. Sensitivity of shear distribution factors; steel girder bridges; single lane loading scenario

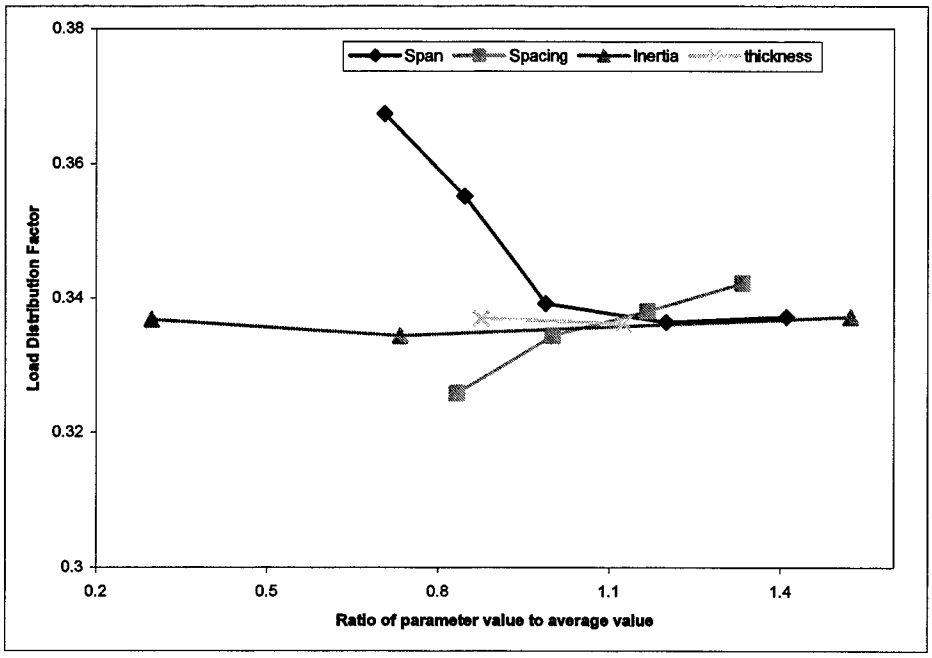


Figure 28. Sensitivity of shear distribution factors; prestressed girder bridges; single lane loading scenario

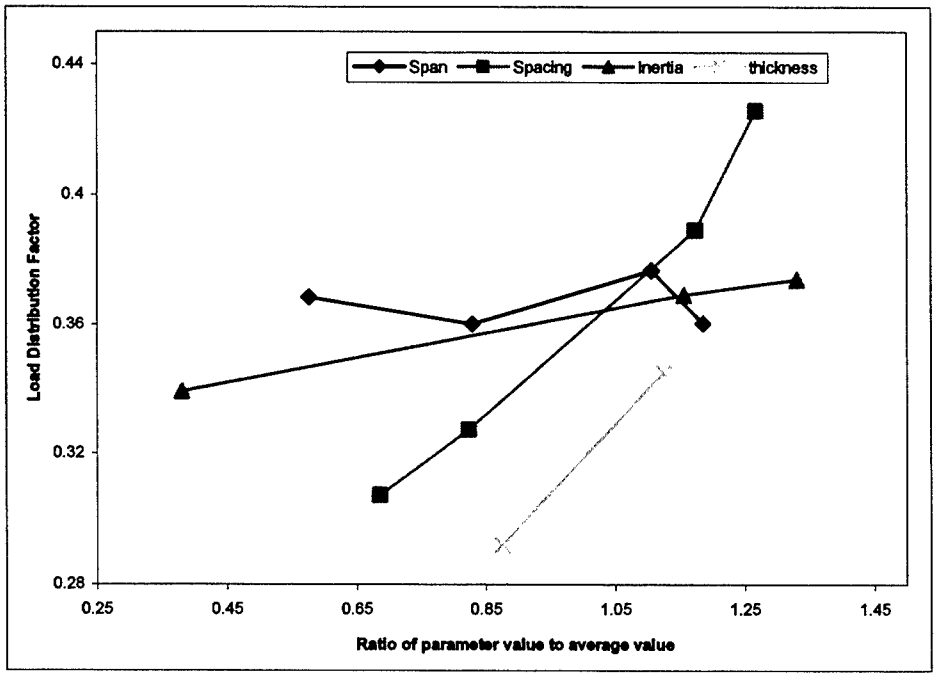


Figure 29. Sensitivity of shear distribution factors; concrete T-beam bridges; single lane loading scenario

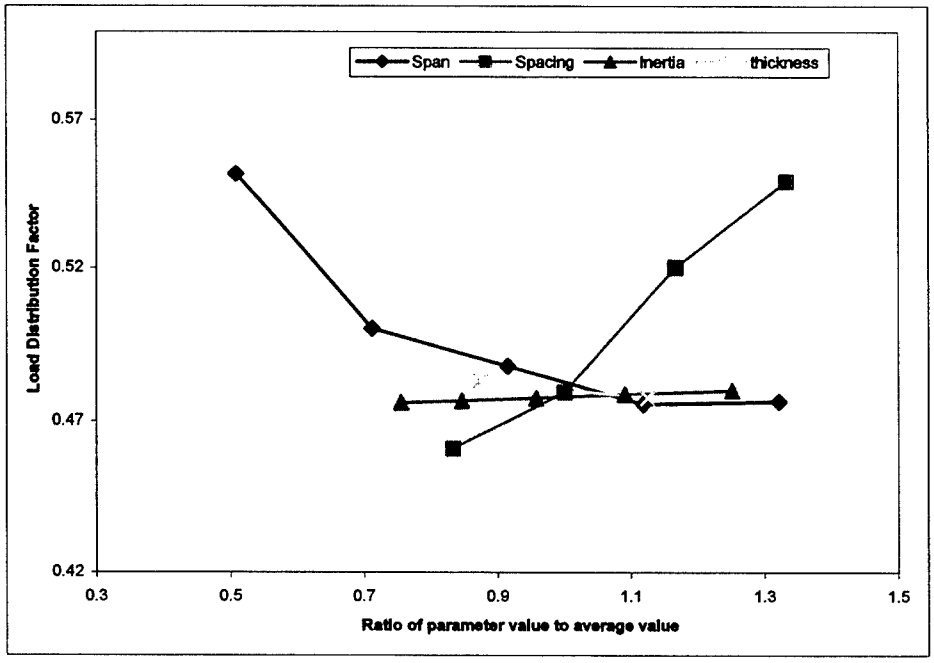


Figure 30. Sensitivity of shear distribution factors; steel girder bridges; multiple lane loading scenario

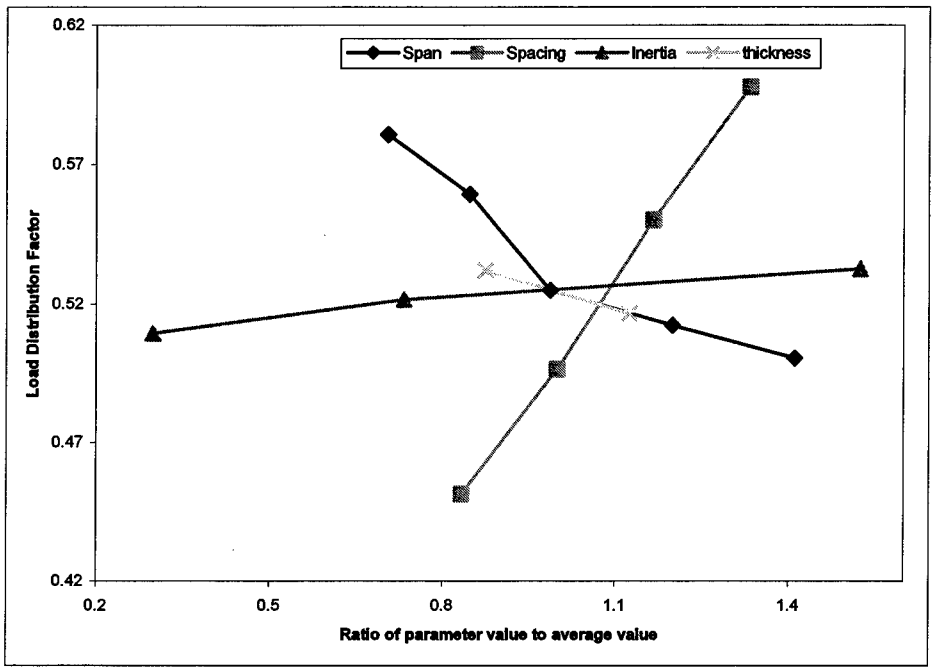


Figure 31. Sensitivity of shear distribution factors; prestressed girder bridges; multiple lane loading scenario

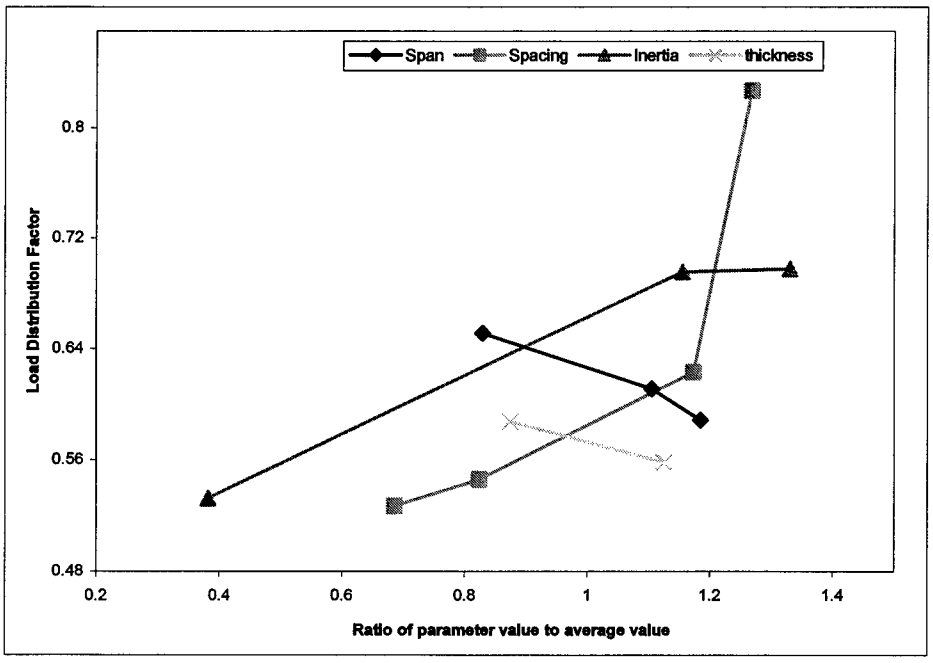


Figure 32. Sensitivity of shear distribution factors; concrete T-beam bridges; multiple lane loading scenario

9 Load Distribution Factor Formulas for Military Vehicles

The load distribution factor values calculated for the three types of bridges and for four different vehicle types were statistically processed using the nonlinear regression analysis feature of the SAS Package (SAS Institute, 1989) to develop the proposed load distribution formulas. As discussed in a previous chapter, separate load distribution factor formulas were developed for 3 different wheeled and 3 different tracked vehicles. However, since some of the vehicles are similar in terms of footprint and therefore load effect on bridges, the results have been grouped as follows: (1) HETS, (2) PLS and HEMMT considered as a group, (3) M1 Tank, (4) M113 and Bradley vehicles considered as a group, and (5) all military vehicles considered as a single group.

The formulas are developed for three types of bridges (steel multi-girder, reinforced concrete T-beam, and prestressed concrete I-beam bridges) separately as well as for all types of bridges considered as a group. For the first four sets of vehicles, the formulas were developed only for the bending moment in the interior girders of a bridge. For this set, there are 20 different formulas. These formulas are listed in Tables 6 through 9. For the case of all military vehicles considered as a group, the formulas were developed separately for: (a) bending moment and shear force values, (b) single lane and multiple lane loading scenarios, and (d) interior and exterior girders. There are 32 different formulas for this case. These formulas are listed in Tables 10 through 13. Tables 12 and 13 provide these formulas for bending moment and shear force, respectively, in the external girders. Part (a) of the tables provides the expressions of the formulas, whereas Part (b) gives the amplification factor that must be applied to the values calculated from the formulas. This amplification factor depends on the size of the overhang on the outside of a girder. If the distribution factor value obtained with the amplification factor for an exterior girder is less than the value for an interior girder, then the distribution factor value for the interior girders should be used to compute the design bending moment and shear force values. It is reiterated here that these formulas should be used with the entire vehicular load effect (i.e. not that from a wheel line as is done by AASHTO). The last columns in these tables also provide the range of applicability of these formulas. These values represent the range of the parameter values in the population of the three different bridge types considered in this study. The last columns in these tables

also provide the range of applicability of these formulas. These values represent the range of the parameter values in the population of the three different ridge types considered in this study.

Table 6
Bending Moment Load Distribution Factor Formulas for Interior Girders; PLS and HEMMT Vehicles

Bridge Type	Lane Loading	Range of Applicability
All Beam Bridges	Single Lane $-0.1+\left(\frac{S}{11.27}\right)^{0.25}\left(\frac{S}{L}\right)^{0.15}\left(\frac{nI}{12Lt^3}\right)^{0.06}$ Multiple Lane $0.086+\left(\frac{S}{7.24}\right)^{0.57}\left(\frac{S}{L}\right)^{0.24}\left(\frac{nI}{12Lt^3}\right)^{0.074}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	Single Lane $0.22+\left(\frac{S}{7.96}\right)^{0.23}\left(\frac{S}{L}\right)^{0.17}\left(\frac{nI}{12Lt^3}\right)^{0.16}$ Multiple Lane $0.16+\left(\frac{S}{13.45}\right)^{0.59}\left(\frac{S}{L}\right)^{0.17}\left(\frac{nI}{12Lt^3}\right)^{0.08}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	Single Lane $-0.53+\left(\frac{S}{1.25}\right)^{0.19}\left(\frac{S}{L}\right)^{0.1}\left(\frac{nI}{12Lt^3}\right)^{0.05}$ Multiple Lane $-0.17+\left(\frac{S}{4.4}\right)^{0.45}\left(\frac{S}{L}\right)^{0.16}\left(\frac{nI}{12Lt^3}\right)^{0.053}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	Single Lane $0.11+\left(\frac{S}{9.3}\right)^{0.73}\left(\frac{S}{L}\right)^{0.3}\left(\frac{nI}{12Lt^3}\right)^{0.045}$ Multiple Lane $0.36+\left(\frac{S}{8.37}\right)^{1.54}\left(\frac{S}{L}\right)^{0.48}\left(\frac{nI}{12Lt^3}\right)^{0.16}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Parameters Description:

S = spacing between girders, ft

L = span length, ft

t = slab thickness, in.

I = moment of inertia of the girder, in.^{4}

n = modular ratio = ratio of the elastic modulus of the girder to that of the slab

Table 7
Bending Moment Load Distribution Factor Formulas for Interior Girders; HETS Vehicle

Bridge Type	Single Lane Loading	Range of Applicability
All Beam Bridges	$0.14+\left(\frac{S}{9.06}\right)^{0.63}\left(\frac{S}{L}\right)^{0.35}\left(\frac{nI}{12Lt^3}\right)^{0.15}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	$0.27+\left(\frac{S}{16}\right)^{0.93}\left(\frac{S}{L}\right)^{0.44}\left(\frac{nI}{12Lt^3}\right)^{0.24}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	$-1.16+1.65(S)^{0.11}\left(\frac{S}{L}\right)^{0.082}\left(\frac{nI}{12Lt^3}\right)^{0.018}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	$0.36+\left(\frac{S}{3.82}\right)^{1.5}\left(\frac{S}{L}\right)^{1.6}\left(\frac{nI}{12Lt^3}\right)^{0.5}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Parameters Description:

S = spacing between girders, ft

L = span length, ft

t = slab thickness, in.

I = moment of inertia of the girder, in.^{4}

n = modular ratio = ratio of the elastic modulus of the girder to that of the slab

Table 8
Bending Moment Load Distribution Factor Formulas for Interior Girders; Abrams Vehicle

Bridge Type	Single Lane Loading	Range of Applicability
All Beam Bridges	$0.24+\left(\frac{S}{12.56}\right)^{1.58}\left(\frac{S}{L}\right)^{0.28}\left(\frac{nI}{12Lt^3}\right)^{0.15}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	$0.095+\left(\frac{S}{69.36}\right)^{0.46}\left(\frac{S}{L}\right)^{0.05}\left(\frac{nI}{12Lt^3}\right)^{0.05}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	$-0.51+\left(\frac{S}{5.77}\right)^{0.3}\left(\frac{S}{L}\right)^{0.034}\left(\frac{nI}{12Lt^3}\right)^{0.02}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	$0.35+\left(\frac{S}{8.81}\right)^{2.47}\left(\frac{S}{L}\right)^{1.02}\left(\frac{nI}{12Lt^3}\right)^{0.28}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Parameters Description:

S = spacing between girders, ft

L = span length, ft

t = slab thickness, in.

I = moment of inertia of the girder, in.^{4}

n = modular ratio = ratio of the elastic modulus of the girder to that of the slab

Table 9
Bending Moment Load Distribution Factor Formulas for Interior Girders; M113 and Bradley Vehicles

Bridge Type	Single Lane Loading	Range of Applicability
All Beam Bridges	$0.24+\left(\frac{S}{11.89}\right)^{1.35}\left(\frac{S}{L}\right)^{0.29}\left(\frac{nI}{12Lt^3}\right)^{0.14}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	$0.27+\left(\frac{S}{22.8}\right)^{0.86}\left(\frac{S}{L}\right)^{0.3}\left(\frac{nI}{12Lt^3}\right)^{0.23}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	$-1.52+1.74(S)^{0.13}\left(\frac{S}{L}\right)^{0.038}\left(\frac{nI}{12Lt^3}\right)^{0.019}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	$0.34+\left(\frac{S}{8.03}\right)^{1.95}\left(\frac{S}{L}\right)^{0.8}\left(\frac{nI}{12Lt^3}\right)^{0.33}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Parameters Description:

S = spacing between girders, ft

L = span length, ft

t = slab thickness, in.

I = moment of inertia of the girder, in.^{4}

n = modular ratio = ratio of the elastic modulus of the girder to that of the slab

Table 10
Bending Moment Load Distribution Factor Formulas for Interior Girders; All Military Vehicles

Bridge Type	Lane Loading	Range of Applicability
All Beam Bridges	Single Lane $0.21+\left(\frac{S}{12.24}\right)^{0.73}\left(\frac{S}{L}\right)^{0.37}\left(\frac{nI}{12Lt^3}\right)^{0.18}$ Multiple Lane $-0.014+\left(\frac{S}{6.91}\right)^{0.54}\left(\frac{S}{L}\right)^{0.19}\left(\frac{nI}{12Lt^3}\right)^{0.06}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	Single Lane $0.3+\left(\frac{S}{18.2}\right)\left(\frac{S}{L}\right)^{0.41}\left(\frac{nI}{12Lt^3}\right)^{0.28}$ Multiple Lane $0.05+\left(\frac{S}{11}\right)^{0.56}\left(\frac{S}{L}\right)^{0.14}\left(\frac{nI}{12Lt^3}\right)^{0.068}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	Single Lane $-0.92+1.23(S)^{0.16}\left(\frac{S}{L}\right)^{0.063}\left(\frac{nI}{12Lt^3}\right)^{0.03}$ Multiple Lane $-0.12+\left(\frac{S}{6.12}\right)^{0.53}\left(\frac{S}{L}\right)^{0.14}\left(\frac{nI}{12Lt^3}\right)^{0.053}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	Single Lane $0.36+\left(\frac{S}{4.57}\right)^{1.63}\left(\frac{S}{L}\right)^{1.55}\left(\frac{nI}{12Lt^3}\right)^{0.44}$ Multiple Lane $0.31+\left(\frac{S}{9.03}\right)^{1.33}\left(\frac{S}{L}\right)^{0.38}\left(\frac{nI}{12Lt^3}\right)^{0.12}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Parameters Description:

S = spacing between girders, ft

L = span length, ft

t = slab thickness, in.

I = moment of inertia of the girder, in.^{4}

n = modular ratio = ratio of the elastic modulus of the girder to that of the slab

Table 11
Shear Load Distribution Factor Formulas for Interior Girders; All Military Vehicles

Bridge Type	Lane Loading	Range of Applicability
All Beam Bridges	Single Lane $-0.12+\left(\frac{S}{9.94}\right)^{0.18}\left(\frac{S}{L}\right)^{0.12}\left(\frac{nI}{12Lt^3}\right)^{0.06}$ Multiple Lane $0.16+\left(\frac{S}{10.17}\right)^{0.61}\left(\frac{S}{L}\right)^{0.24}\left(\frac{nI}{12Lt^3}\right)^{0.073}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	Single Lane $0.22+\left(\frac{S}{118.7}\right)^{0.23}\left(\frac{S}{L}\right)^{0.35}\left(\frac{nI}{12Lt^3}\right)^{0.14}$ Multiple Lane $0.14+\left(\frac{S}{18.78}\right)^{0.5}\left(\frac{S}{L}\right)^{0.15}\left(\frac{nI}{12Lt^3}\right)^{0.057}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	Single Lane $-0.8+1.2(S)^{0.16}\left(\frac{S}{L}\right)^{0.08}\left(\frac{nI}{12Lt^3}\right)^{0.034}$ Multiple Lane $-0.75+\left(\frac{S}{1.41}\right)^{0.25}\left(\frac{S}{L}\right)^{0.034}\left(\frac{nI}{12Lt^3}\right)^{0.012}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	Single Lane $0.32+\left(\frac{S}{11.79}\right)\left(\frac{S}{L}\right)^{0.95}\left(\frac{nI}{12Lt^3}\right)^{0.35}$ Multiple Lane $0.08+\left(\frac{S}{7.56}\right)^{0.56}\left(\frac{S}{L}\right)^{0.25}\left(\frac{nI}{12Lt^3}\right)^{0.079}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Parameters Description:

S = spacing between girders, ft

L = span length, ft

t = slab thickness, in.

I = moment of inertia of the girder, in.^{4}

n = modular ratio = ratio of the elastic modulus of the girder to that of the slab

Table 12a
Bending Moment Load Distribution Factor Formulas for Exterior Girders; All Military Vehicles

Bridge Type	Lane Loading	Range of Applicability
All Beam Bridges	Single Lane $-0.51+\left(\frac{S}{6.1}\right)^{0.22}\left(\frac{S}{L}\right)^{0.004}\left(\frac{nI}{12Lt^3}\right)^{0.005}$ Multiple Lane $0.22+\left(\frac{S}{25.43}\right)^{1.16}\left(\frac{S}{L}\right)^{-0.14}\left(\frac{nI}{12Lt^3}\right)^{-0.07}$	$2.17' \le S \le 12'$ $12' \le L \le 205'$ $4.42'' \le t \le 12''$ $234\ in.^4 \le I \le 733{,}320\ in.^4$
Steel	Single Lane $-0.11+\left(\frac{S}{19.6}\right)^{0.43}\left(\frac{S}{L}\right)^{0.01}\left(\frac{nI}{12Lt^3}\right)^{0.005}$ Multiple Lane $-0.03+\left(\frac{S}{16.84}\right)^{0.7}\left(\frac{S}{L}\right)^{-0.047}\left(\frac{nI}{12Lt^3}\right)^{-0.}$	$2.17' \le S \le 12'$ $20' \le L \le 205'$ $4.42'' \le t \le 12''$ $234\ in.^4 \le I \le 287{,}125\ in.^4$
Prestressed	Single Lane $-0.03+\left(\frac{S}{36}\right)^{0.41}\left(\frac{S}{L}\right)^{-0.02}\left(\frac{nI}{12Lt^3}\right)^{-0.002}$ Multiple Lane $0.25+\left(\frac{S}{27.53}\right)^{1.15}\left(\frac{S}{L}\right)^{-0.097}\left(\frac{nI}{12Lt^3}\right)^{-0.0}$	$3.21' \le S \le 10.5'$ $18.75' \le L \le 136'$ $5'' \le t \le 9''$ $9{,}599\ in.^4 \le I \le 733{,}320\ in.^4$
T-Beam	Single Lane $0.23+\left(\frac{S}{42.83}\right)^{0.64}\left(\frac{S}{L}\right)^{0.06}\left(\frac{nI}{12Lt^3}\right)^{-0.005}$ Multiple Lane $0.3+\left(\frac{S}{25.41}\right)^{1.24}\left(\frac{S}{L}\right)^{-0.16}\left(\frac{nI}{12Lt^3}\right)^{-0.07}$	$4.75' \le S \le 9.33'$ $12' \le L \le 78'$ $5'' \le t \le 9''$ $3{,}267\ in.^4 \le I \le 567{,}348\ in.^4$

Table 12b
Exterior Girders Amplification Factors to Be Applied to the Formulas in Table 12a for Different Overhang Values

Loading Scenario	Overhang, ft			
	1	2	3	4
Single Lane	1	1.12	1.24	1.36
Multiple Lane	1	1	1.1	1.2

Parameter descriptions are the same as for previous tables

Table 13a
Shear Load Distribution Factor Formulas for Exterior Girders; All Military Vehicles

Bridge Type	Lane Loading	Range of Applicability
All Beam Bridges	Single Lane $-0.74+1.065(S)^{0.12}\left(\frac{S}{L}\right)^{0.03}\left(\frac{nI}{12Lt^3}\right)^{0.01}$ Multiple Lane $0.1+\left(\frac{S}{33.08}\right)^{0.89}\left(\frac{S}{L}\right)^{-0.23}\left(\frac{nI}{12Lt^3}\right)^{-0.056}$	2.17' ≤ S ≤ 12' 12' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 733,320 in.^{4}
Steel	Single Lane $-1.18+1.7(S)^{0.07}\left(\frac{S}{L}\right)^{0.048}\left(\frac{nI}{12Lt^3}\right)^{0.017}$ Multiple Lane $-0.5+\left(\frac{S}{9.06}\right)^{0.39}\left(\frac{S}{L}\right)^{-0.079}\left(\frac{nI}{12Lt^3}\right)^{-0.017}$	2.17' ≤ S ≤ 12' 20' ≤ L ≤ 205' 4.42" ≤ t ≤ 12" 234 in.^{4} ≤ I ≤ 287,125 in.^{4}
Prestressed	Single Lane $-0.22+\left(\frac{S}{25.17}\right)^{0.28}\left(\frac{S}{L}\right)^{-0.01}\left(\frac{nI}{12Lt^3}\right)^{-0.01}$ Multiple Lane $0.26+\left(\frac{S}{40}\right)^{1.33}\left(\frac{S}{L}\right)^{-0.42}\left(\frac{nI}{12Lt^3}\right)^{-0.06}$	3.21'≤S≤ 10.5' 18.75' ≤ L ≤ 136' 5" ≤ t ≤ 9" 9,599 in.^{4} ≤ I ≤ 733,320 in.^{4}
T-Beam	Single Lane $-0.71+\left(\frac{S}{1.81}\right)^{0.15}\left(\frac{S}{L}\right)^{0.01}\left(\frac{nI}{12Lt^3}\right)^{0.006}$ Multiple Lane $0.16+\left(\frac{S}{25.74}\right)^{0.85}\left(\frac{S}{L}\right)^{-0.12}\left(\frac{nI}{12Lt^3}\right)^{-0.05}$	4.75' ≤ S ≤ 9.33' 12' ≤ L ≤ 78' 5" ≤ t ≤ 9" 3,267 in.^{4} ≤ I ≤ 567,348 in.^{4}

Table 13b
Exterior Girders Amplification Factors to be applied to the formulas in Table 13a for different overhang values

Loading Scenario	Overhang (ft)			
	1'	2'	3'	4'
Single Lane	1	1.12	1.24	1.36
Multiple Lane	1.1	1.2	1.3	1.4

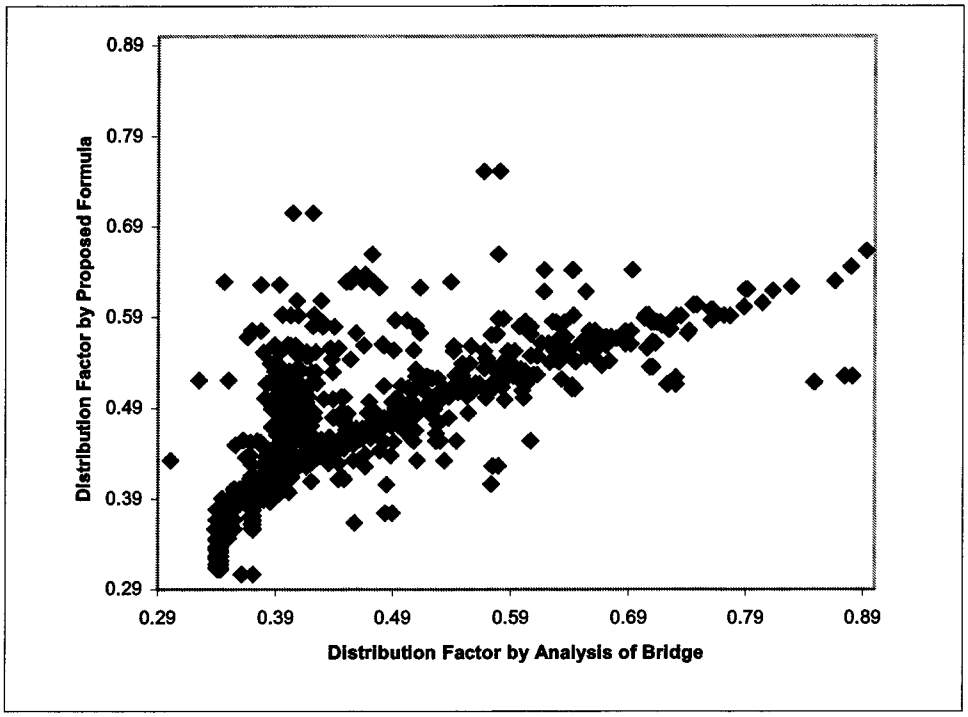
Parameter descriptions are the same as for previous tables

10 Comparison of Distribution Factors Calculated by New Formulas and Direct Bridge Analysis

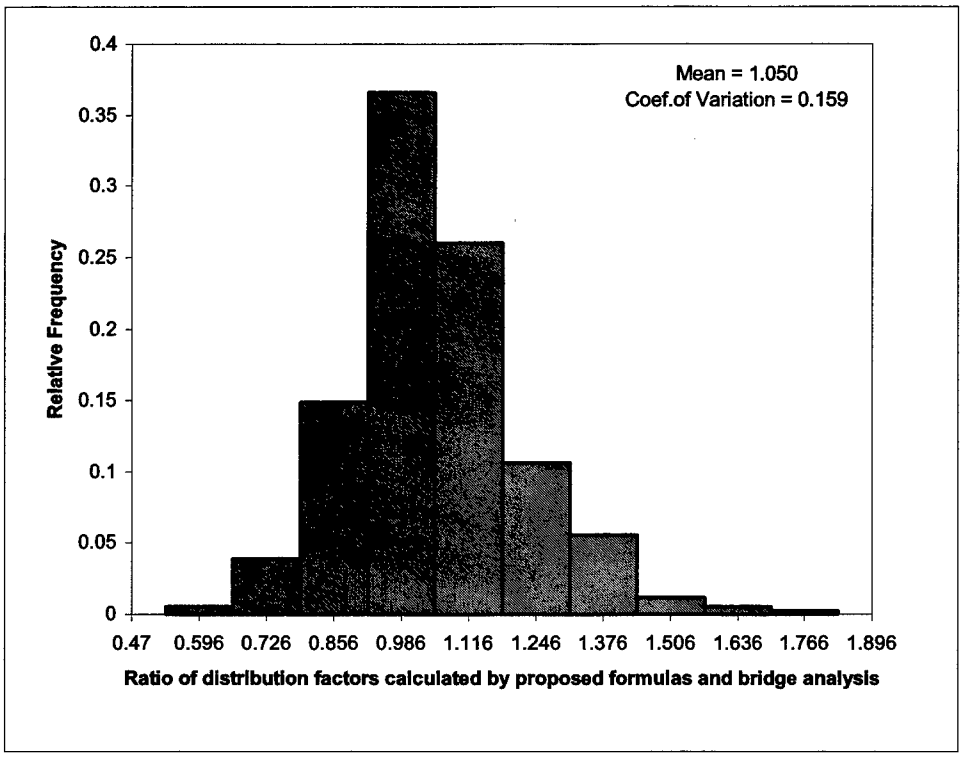
To test the accuracy of the goodness-of-fit of these formulas with respect to the calculated distribution factor values, Figures 33 through 84 have been created. Here each figure pertains to a formula in Table 6 through 13. The following table lists the figures numbers that are associated with different tables numbers. For each set of figures, the table also identifies the type of vehicle (e.g., PLS and HEMMT, HETS, Abrams, M113 and Bradley, and All vehicles), load effect (e.g., bending moment or shear force), and beam location (i.e., interior or exterior) to which the figure set pertains.

Table No.	Figure No.	Vehicle Type	Load Effect	Beam Location
6	33 through 40	PLS and HEMMT	Bending Moment	Interior
7	41 through 44	HETS	Bending Moment	Interior
8	45 through 48	Abrams	Bending Moment	Interior
9	49 through 52	M113 and Bradley	Bending Moment	Interior
10	53 through 60	All Types	Bending moment	Interior
11	61 through 68	All types	Shear Force	Interior
12	69 through76	All Types	Bending Moment	Exterior
13	77 through 84	All Types	Shear Force	Exterior

Part (a) of each figure plots the value of distribution factor calculated by the formula against the value obtained by an actual bridge analysis. Each point in the plot represents a bridge in the data set. A perfectly straight line with a slope of one implies a perfect fit. It is seen that some formulas predict a better fit with a smaller scatter from the 45-degrees straight line than other. The formulas representing a diverse group of vehicles and/or several types of bridges collectively usually have a larger scatter. This is also apparent from the histograms shown in part (b) of the figures. In these figures, the histograms are for the variable of the ratio of the distribution factor calculated by the formula to the one calculated by actual analysis of the bridge. On the histogram figures are also shown the mean and coefficient of variation values of this ratio. A narrow histogram with the mean value close to 1.0 and a low coefficient of variation value indicates a good fit between the analysis and the proposed formula. Such a good fit is usually seen for the cases of a type of vehicle on a particular type of bridge. For example for the HETS vehicle, the mean and coefficient of variation values, respectively, are 1.002 and 4.7 percent for steel bridges (Figure 42), 1.023 and 10.5 percent for prestressed concrete bridges (Figure 43), and 1.008 and 6.3 percent for the concrete T-beam bridges (Figure 44). If the results of all bridge types are lumped together, then for HETS vehicle the mean and coefficient of variation values are 1.004 and 10.7 percent (Figure 41). Concrete T-beam bridges usually have higher variations as indicated by the coefficient of variation values. The coefficient of variation of the bending moment distribution factor ratio for the T-beam concrete bridge is usually higher than for the other types of bridges. Including more types of bridges with different types of vehicles would likely increase the coefficient of variation. In general, the coefficients of variation of the shear force distribution factors tend to be higher than that of the bending moment. A relatively large coefficient of variation value implies that the use of the proposed distribution formula might provide values that could be different from the one calculated by a detailed bridge analysis.

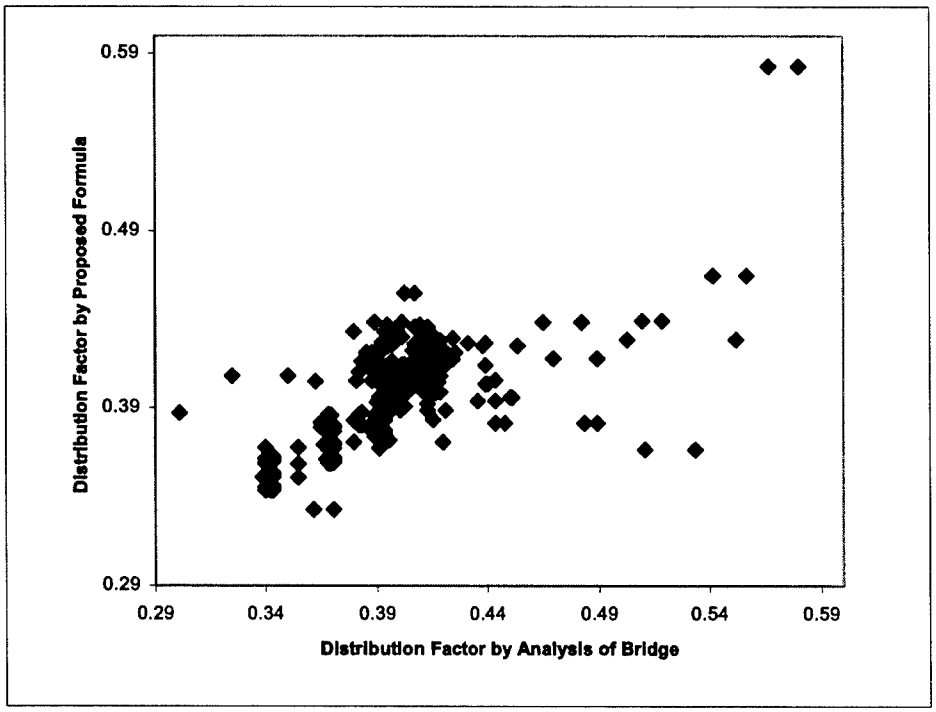


a. Distribution factor

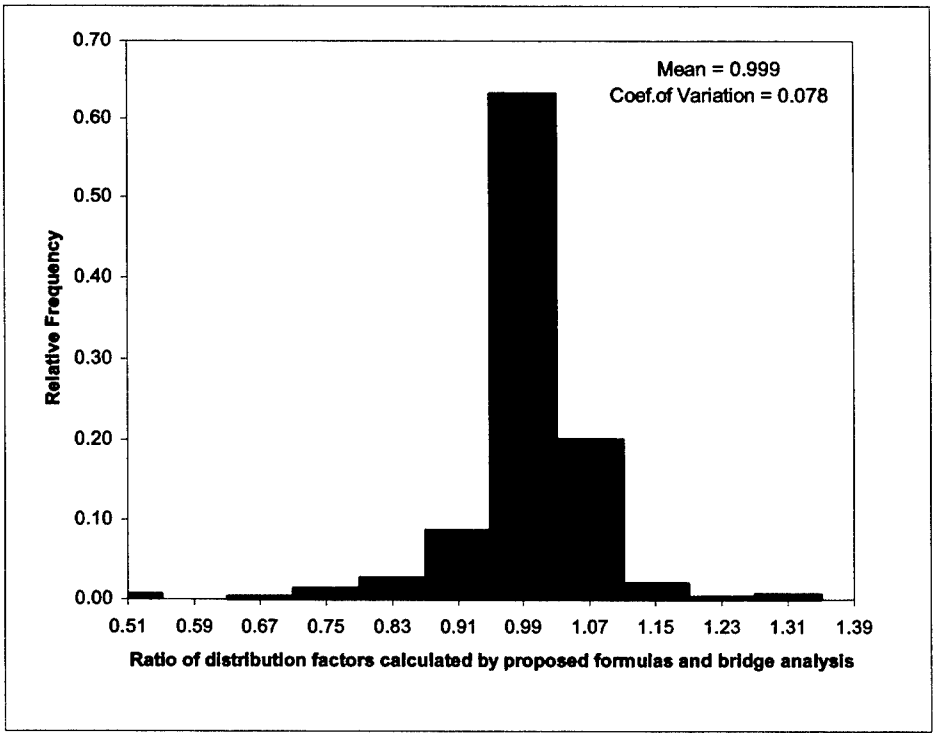


b. Ratio of distribution factors

Figure 33. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, all beam bridges, bending moment in interior girders for single lane

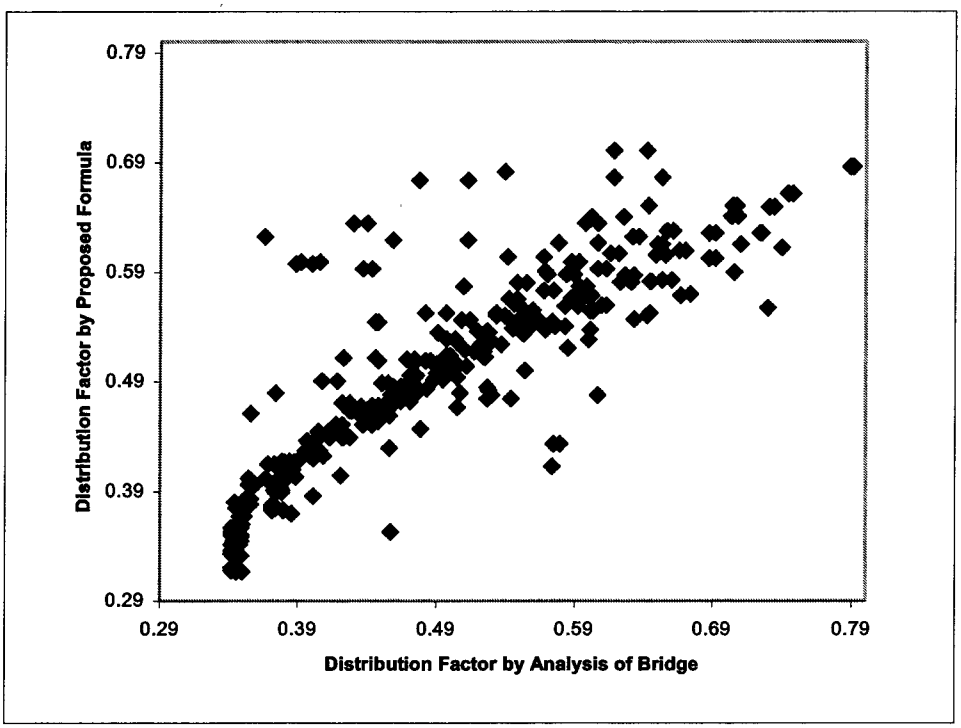


a. Distribution factor

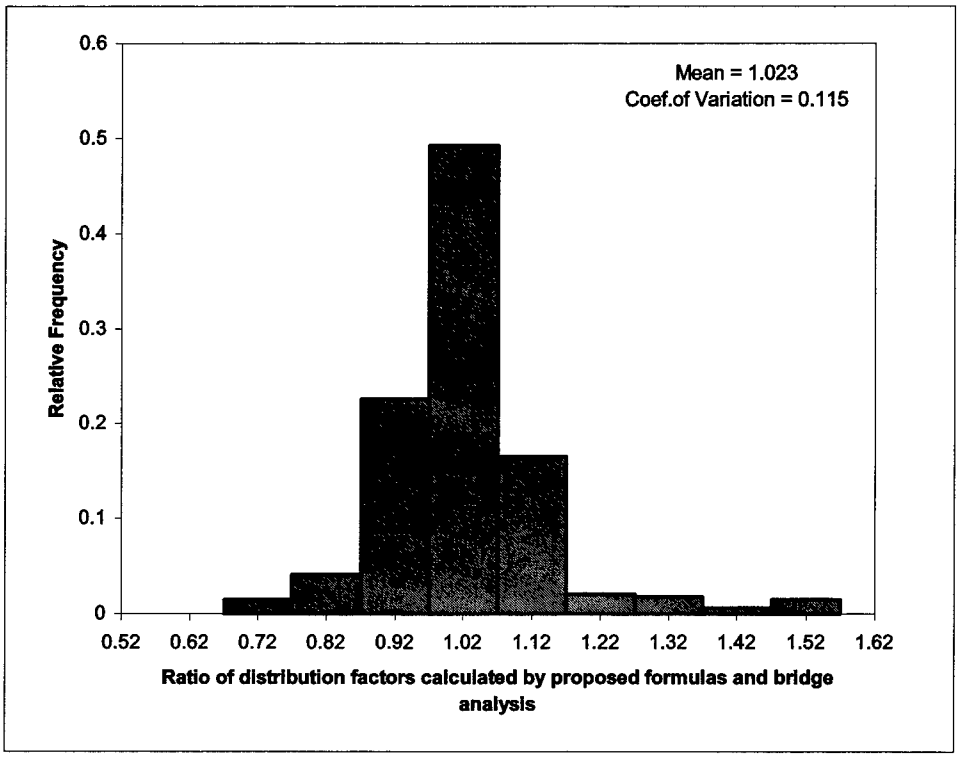


b. Ratio of distribution factors

Figure 34. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, steel girder, bending moment in interior girders for single lane

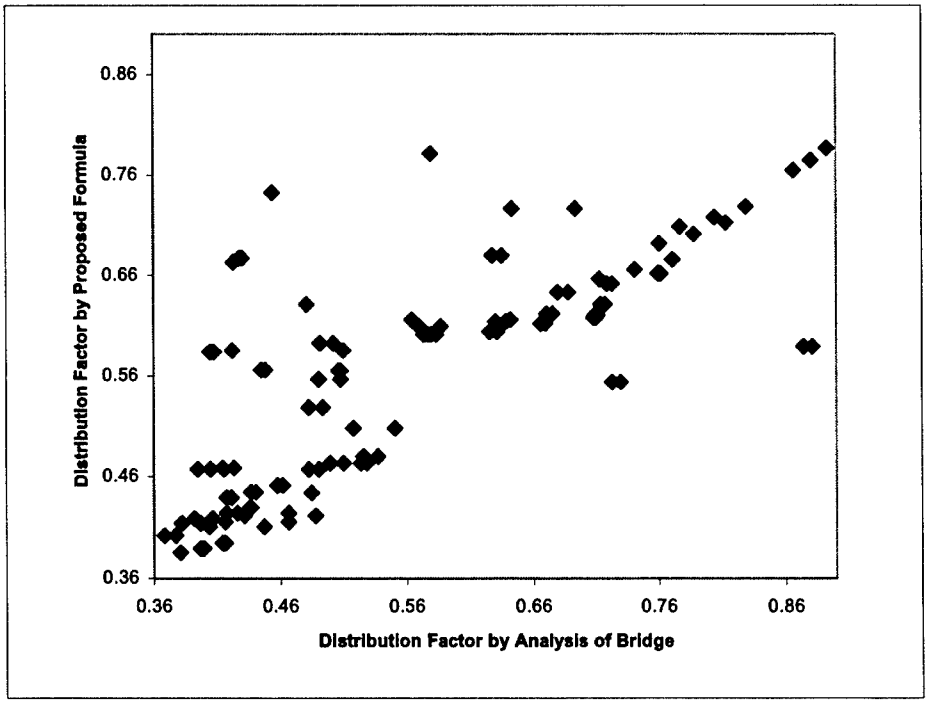


a. Distribution factor

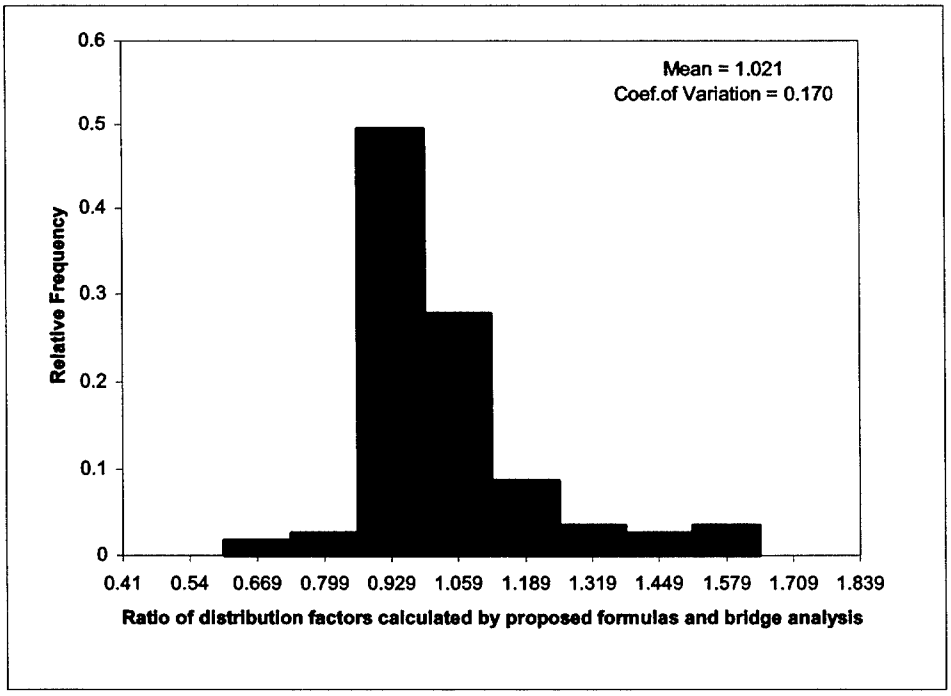


b. Ratio of distribution factors

Figure 35. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, prestressed girder, bending moment in interior girders for single lane

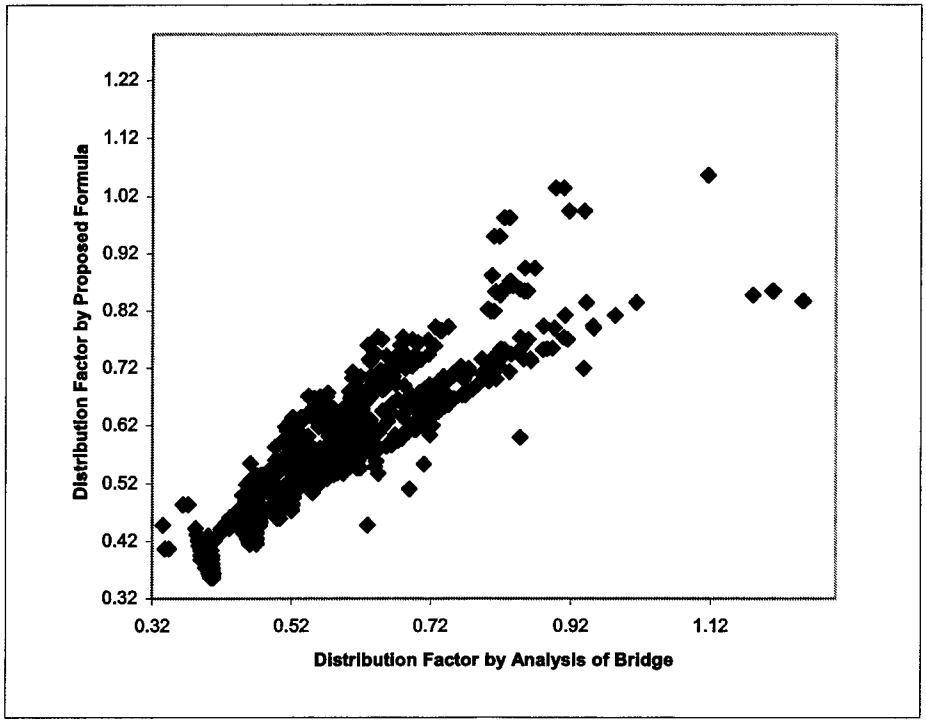


a. Distribution factor

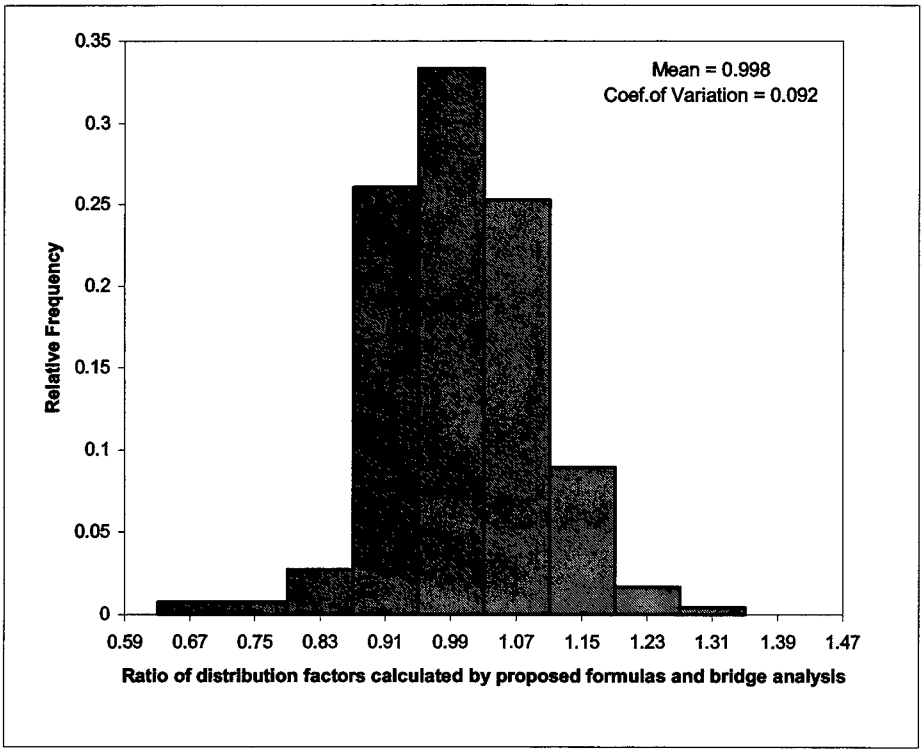


b. Ratio of distribution factors

Figure 36. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, concrete T-beam, bending moment in interior girders for single lane

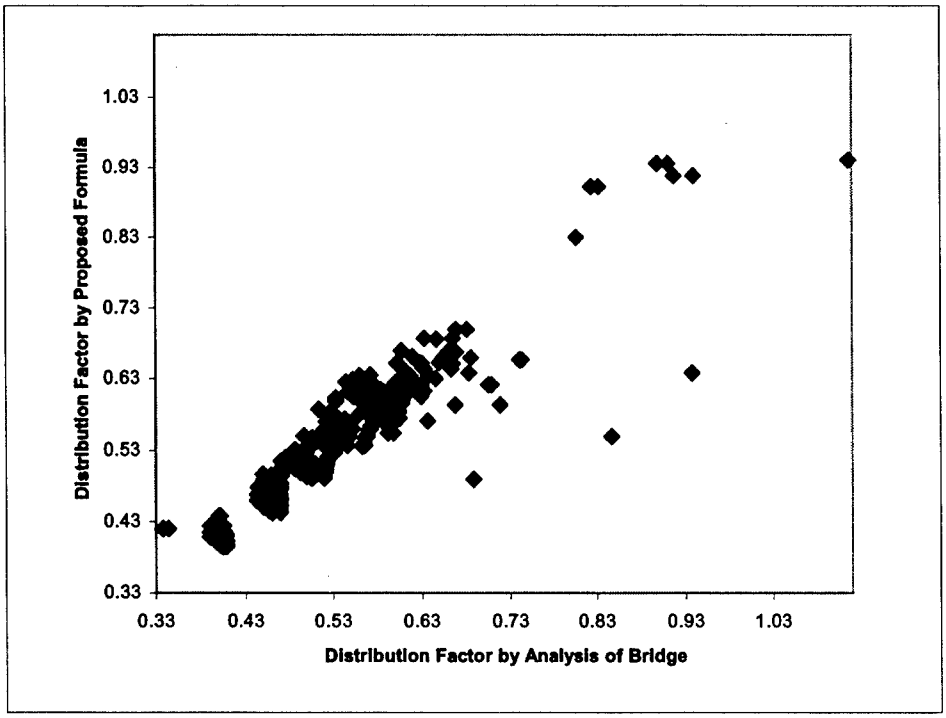


a. Distribution factor

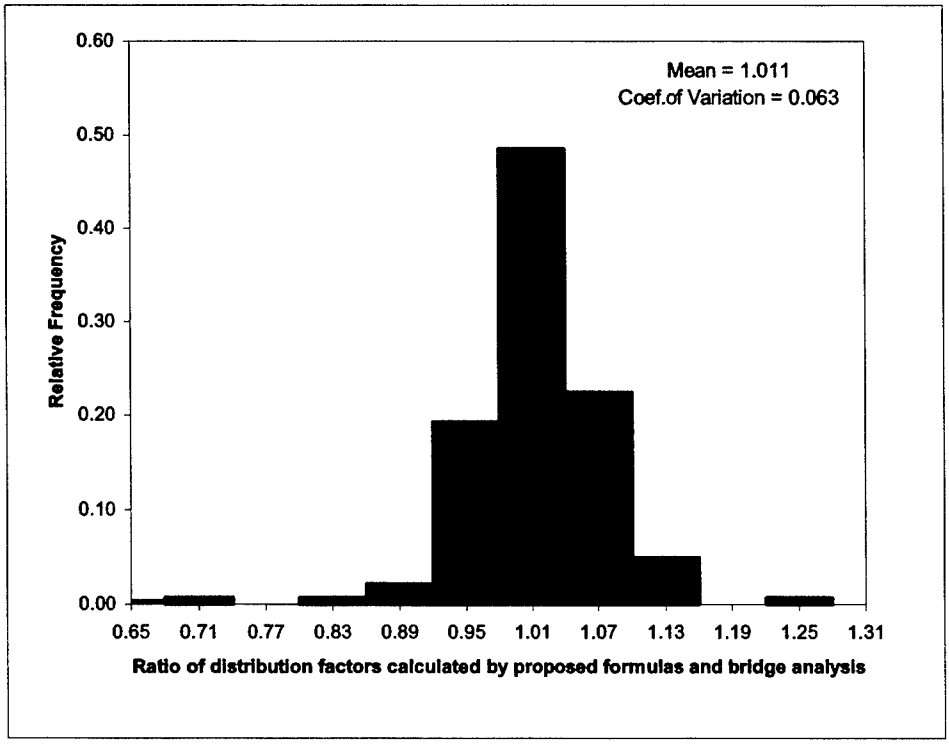


b. Ratio of distribution factors

Figure 37. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, all beam bridges, bending moment in interior girders for multiple lane

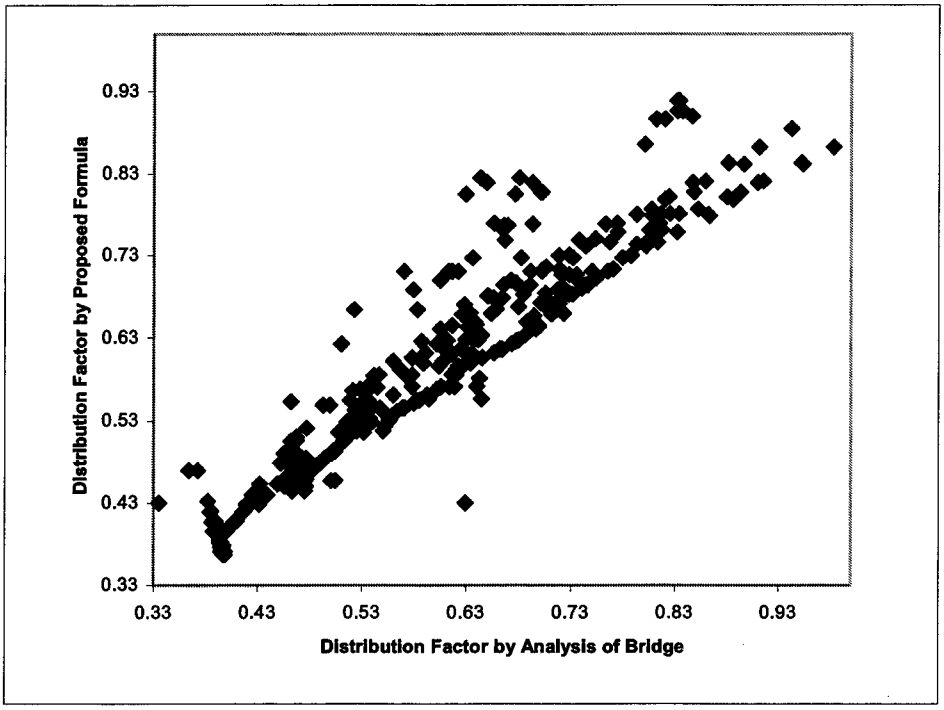


a. Distribution factor

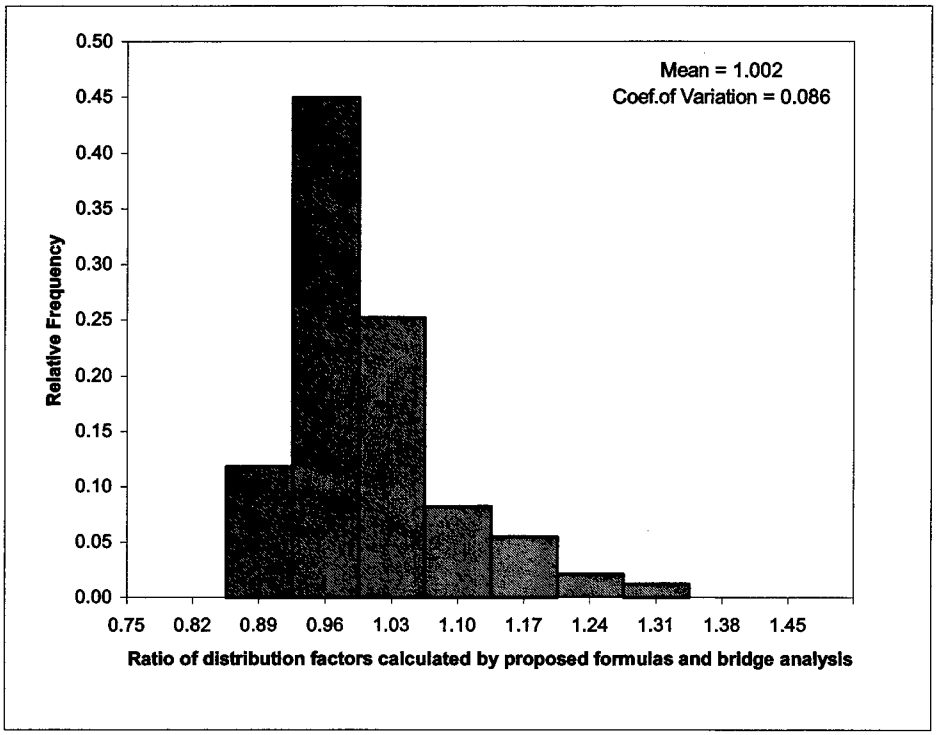


b. Ratio of distribution factors

Figure 38. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, steel girder, bending moment in interior girders for multiple lane

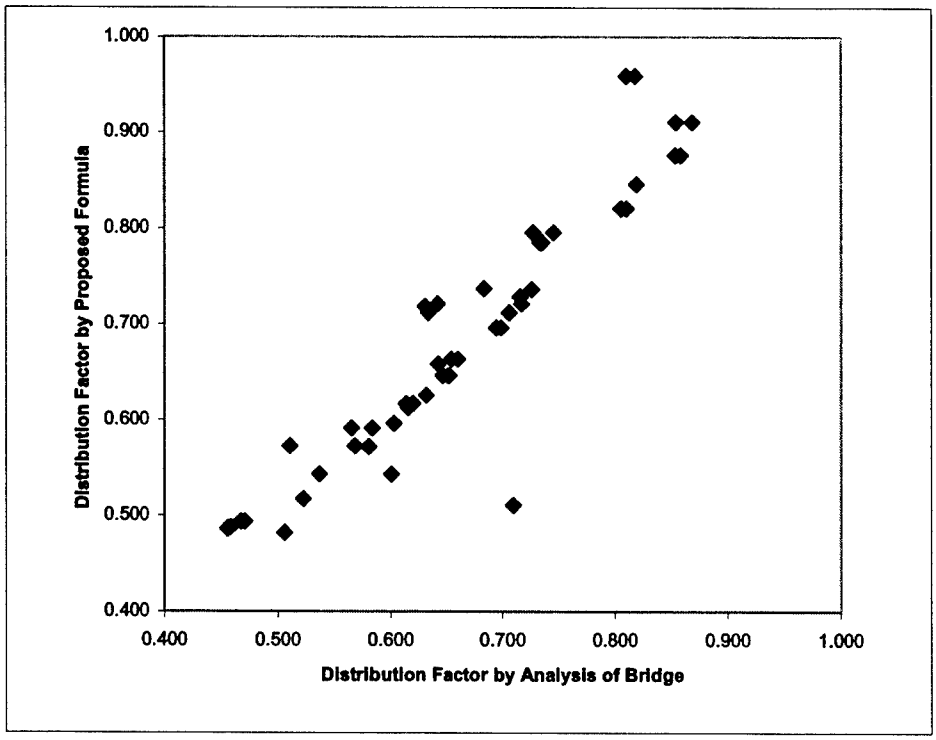


a. Distribution factor

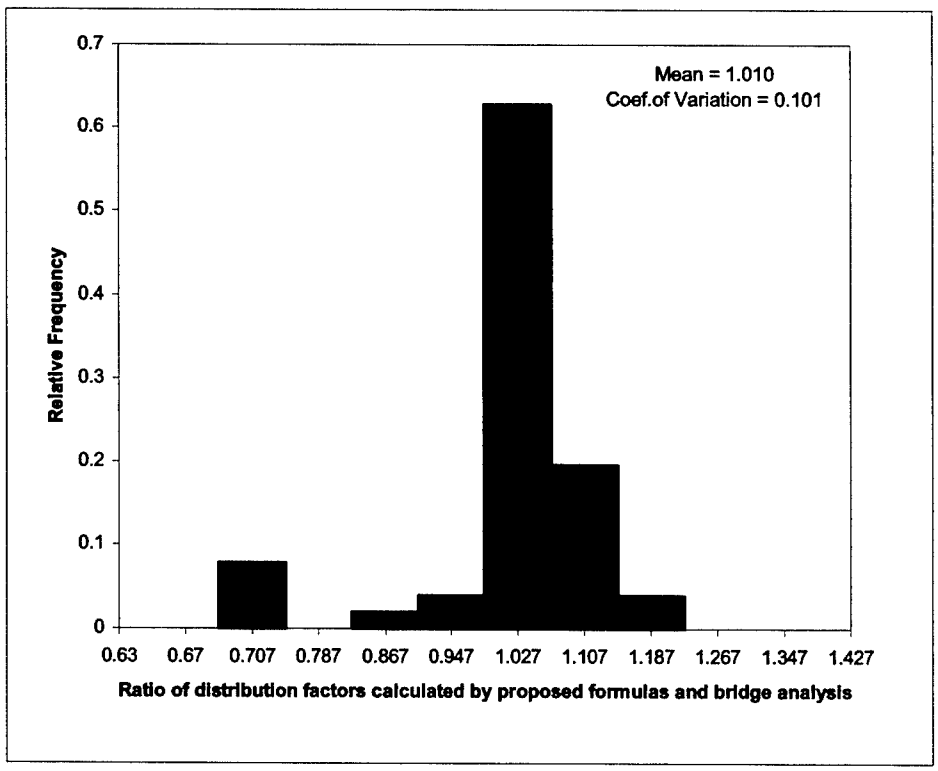


b. Ratio of distribution factors

Figure 39. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, prestressed girder, bending moment in interior girders for multiple lane

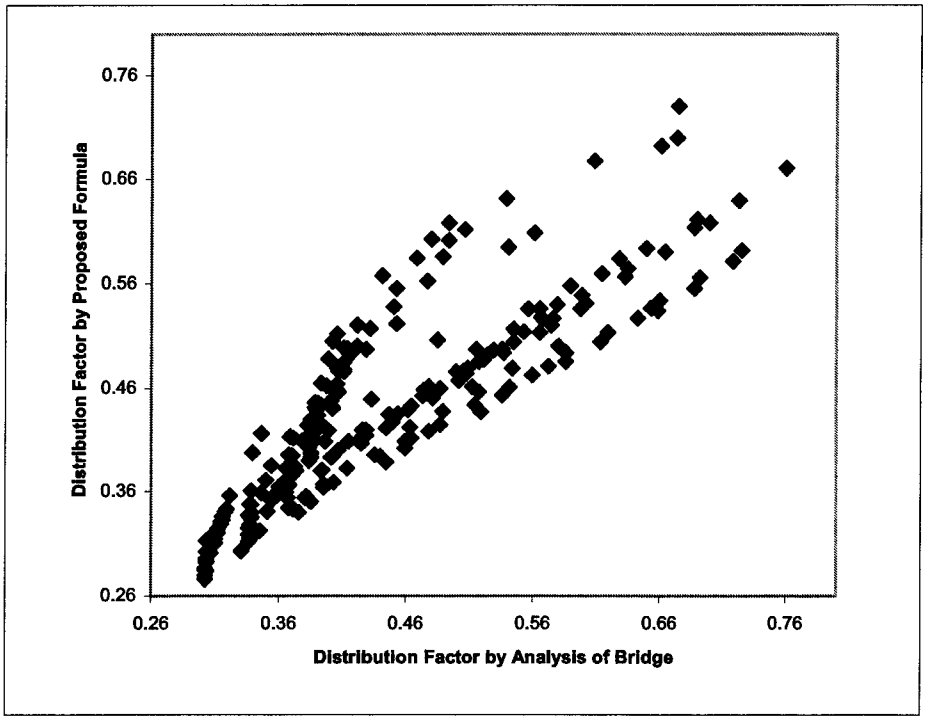


a. Distribution factor

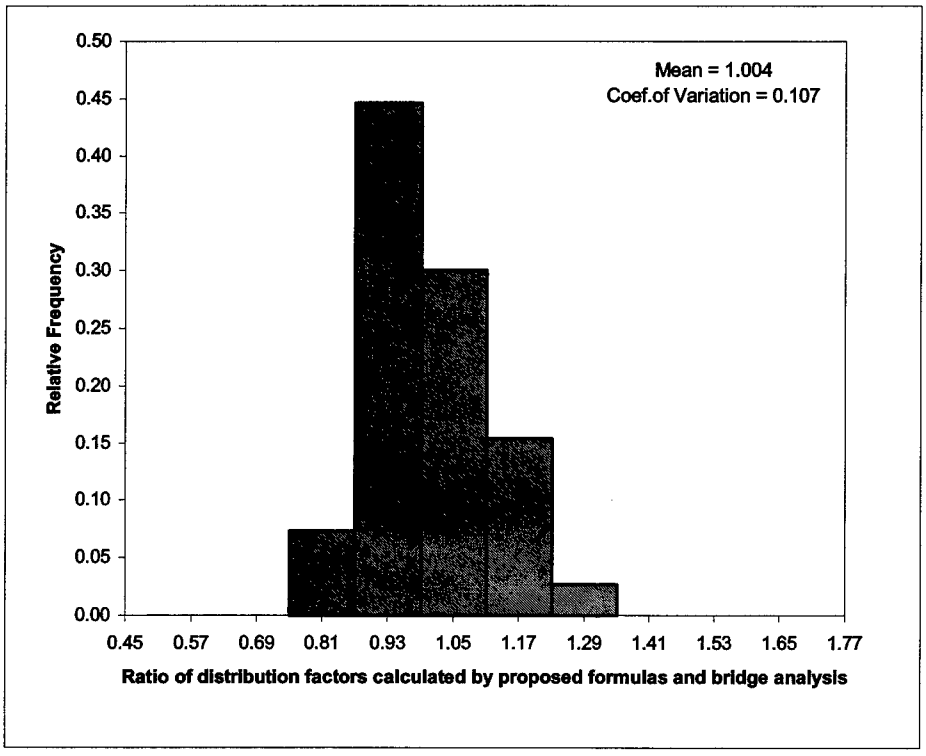


b. Ratio of distribution factors

Figure 40. Comparison of distribution factors calculated by proposed formulas and bridge analysis for PLS and HEMMT vehicles, concrete T-beam, bending moment in interior girders for multiple lane

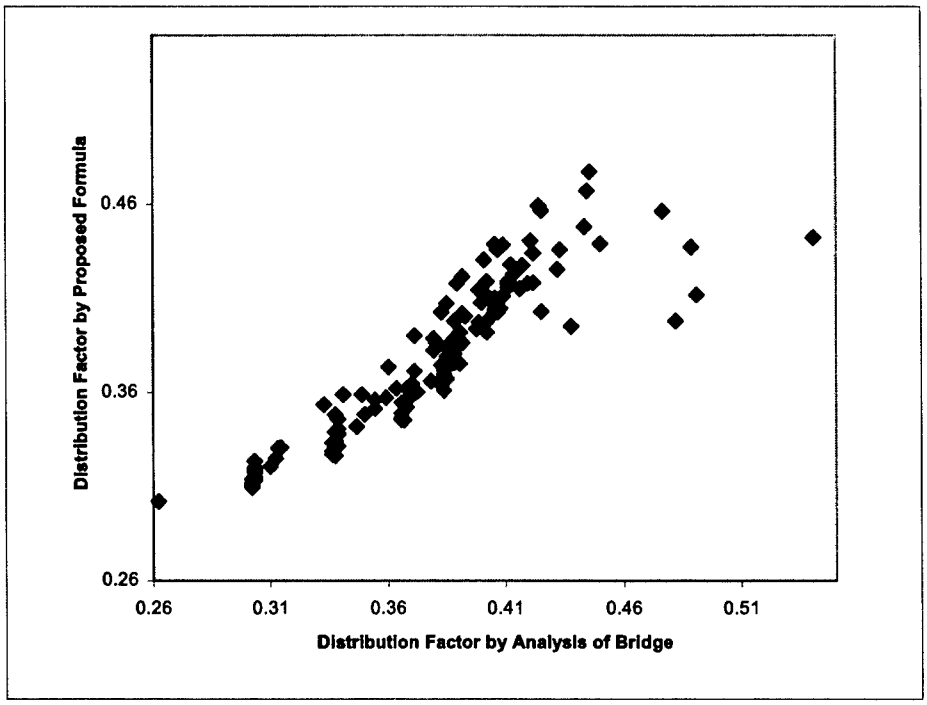


a. Distribution factor

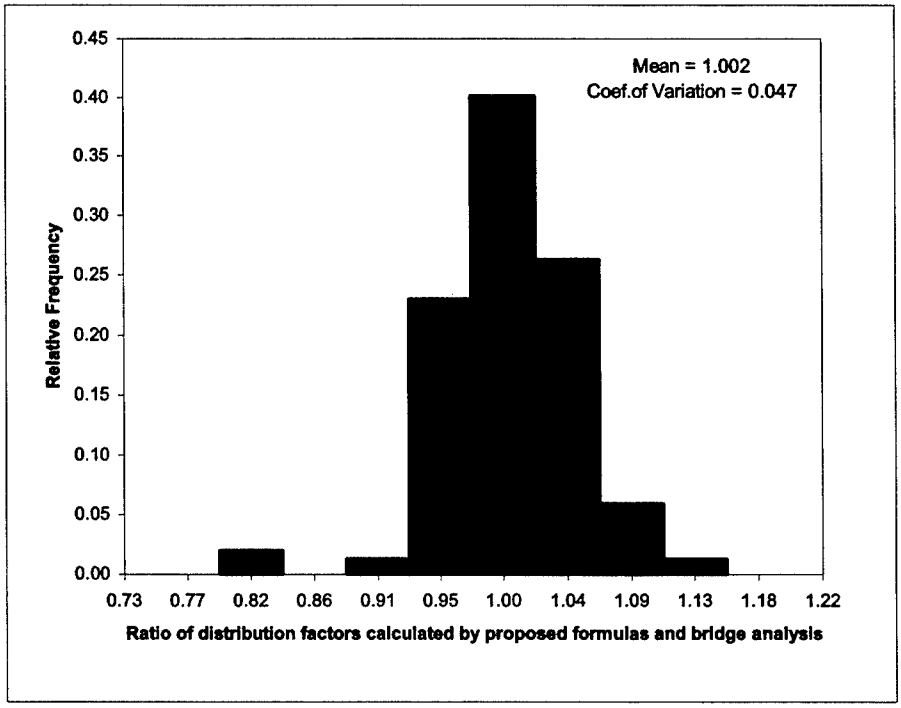


b. Ratio of distribution factors

Figure 41. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, all beam bridges, bending moment in interior girders for single lane

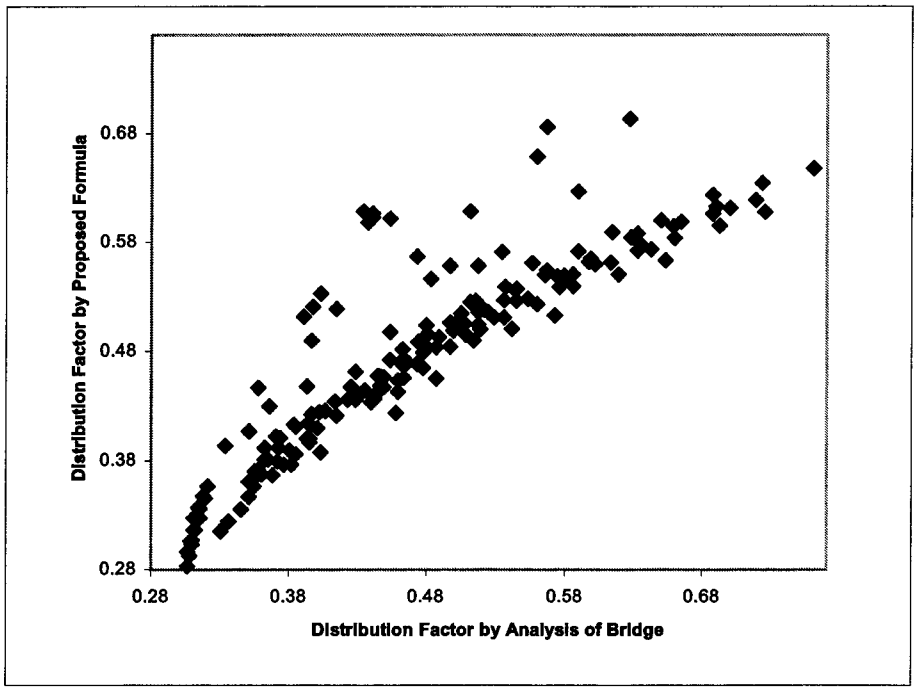


a. Distribution factor

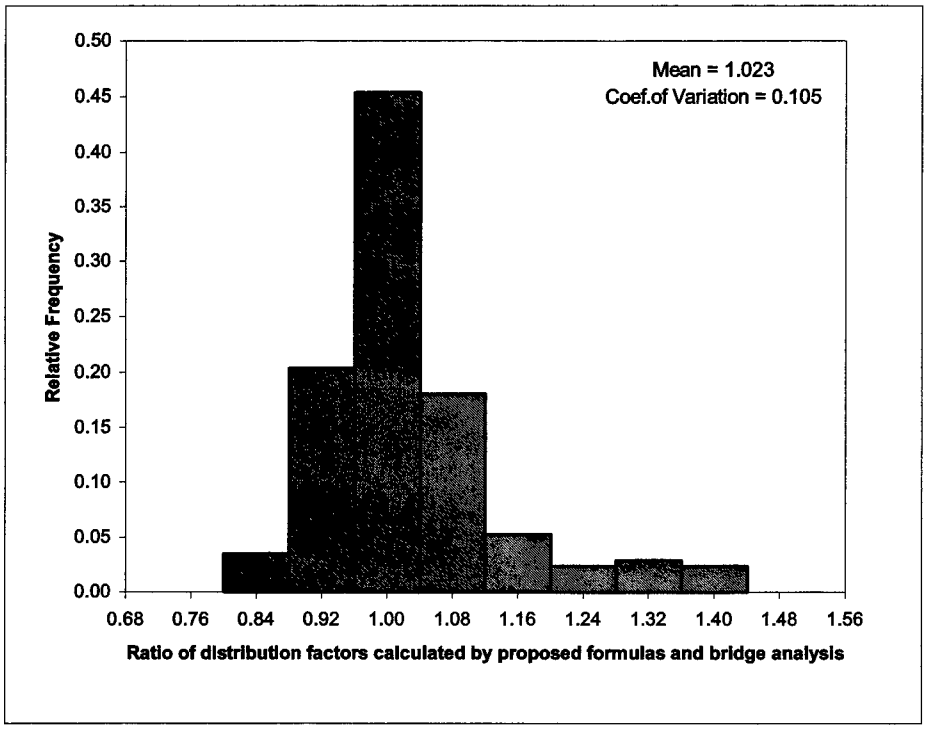


b. Ratio of distribution factors

Figure 42. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, steel girder, bending moment in interior girders for single lane

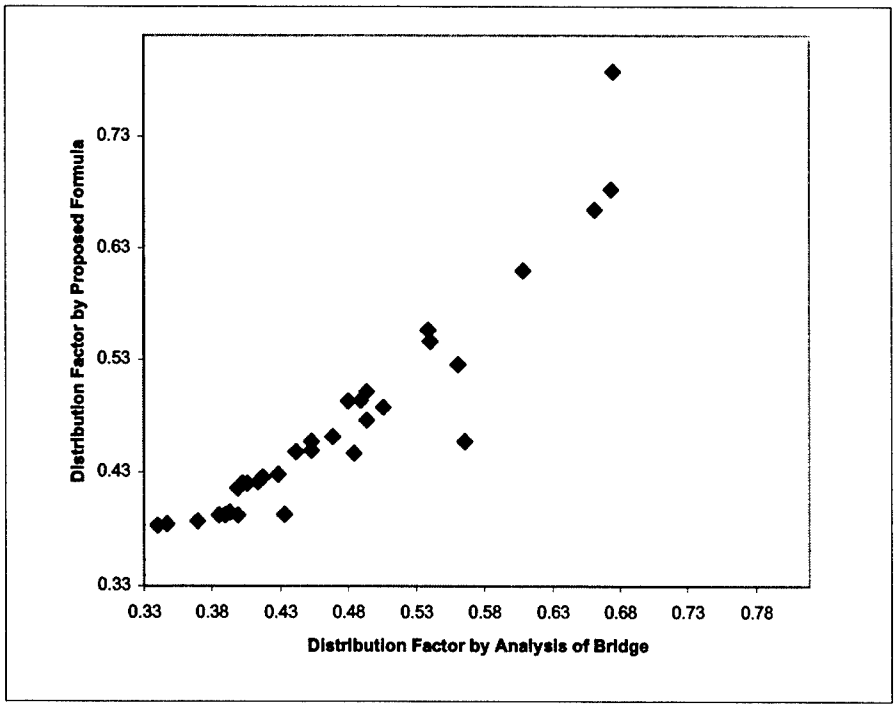


a. Distribution factor

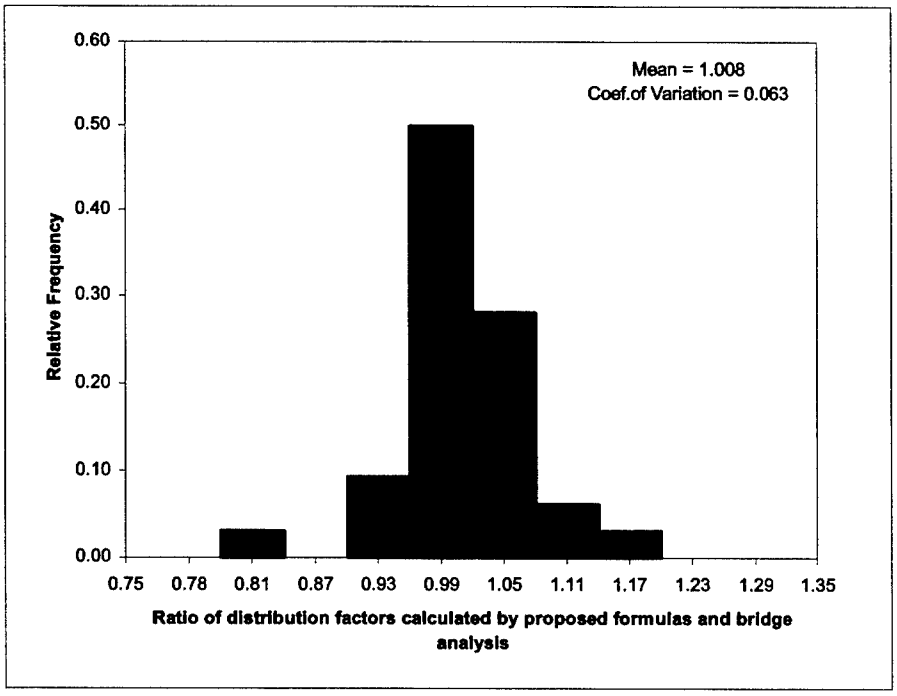


b. Ratio of distribution factors

Figure 43. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, prestressed girder, bending moment in interior girders for single lane

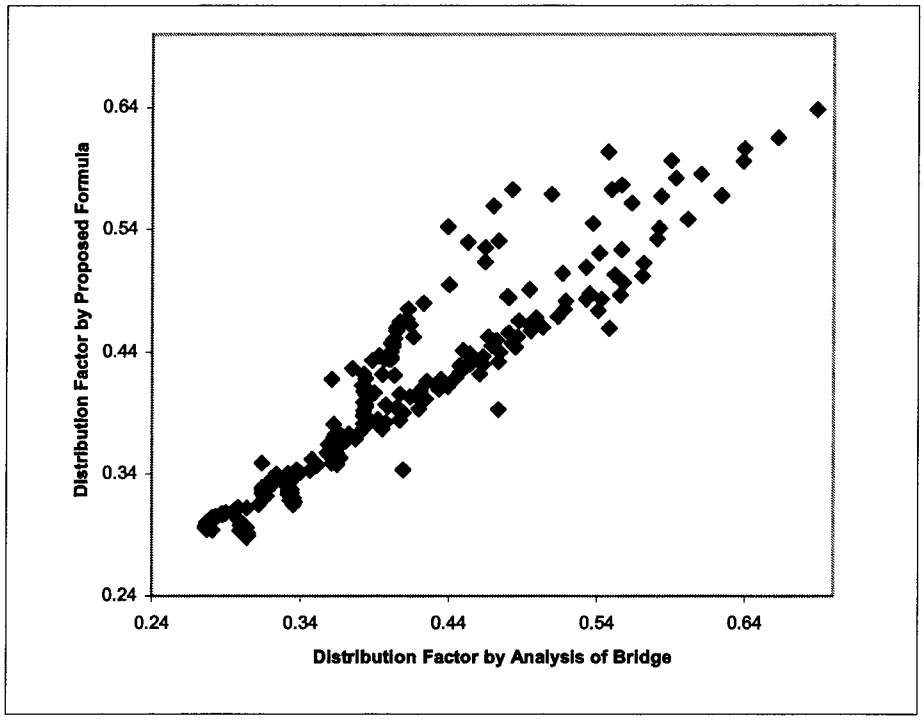


a. Distribution factor

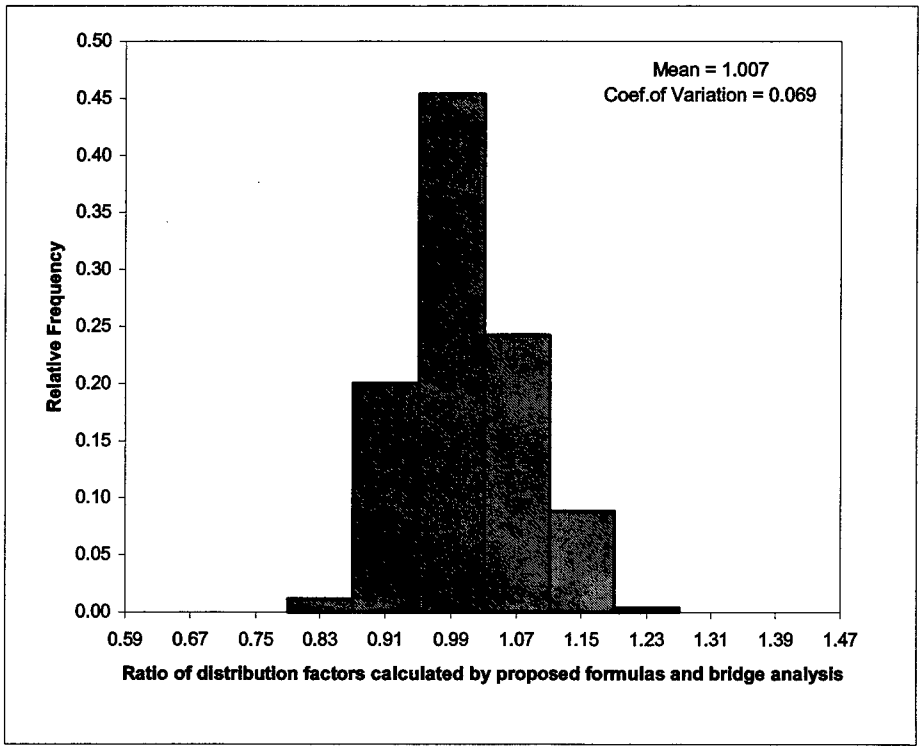


b. Ratio of distribution factors

Figure 44. Comparison of distribution factors calculated by proposed formulas and bridge analysis for HETS vehicle, concrete T-beam, bending moment in interior girders for single lane

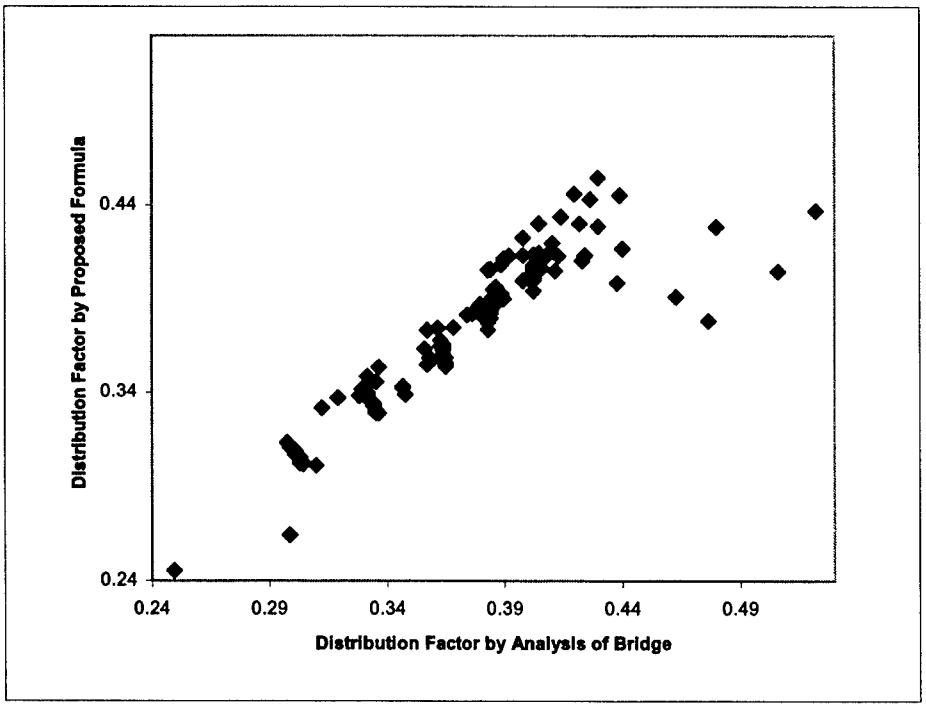


a. Distribution factor

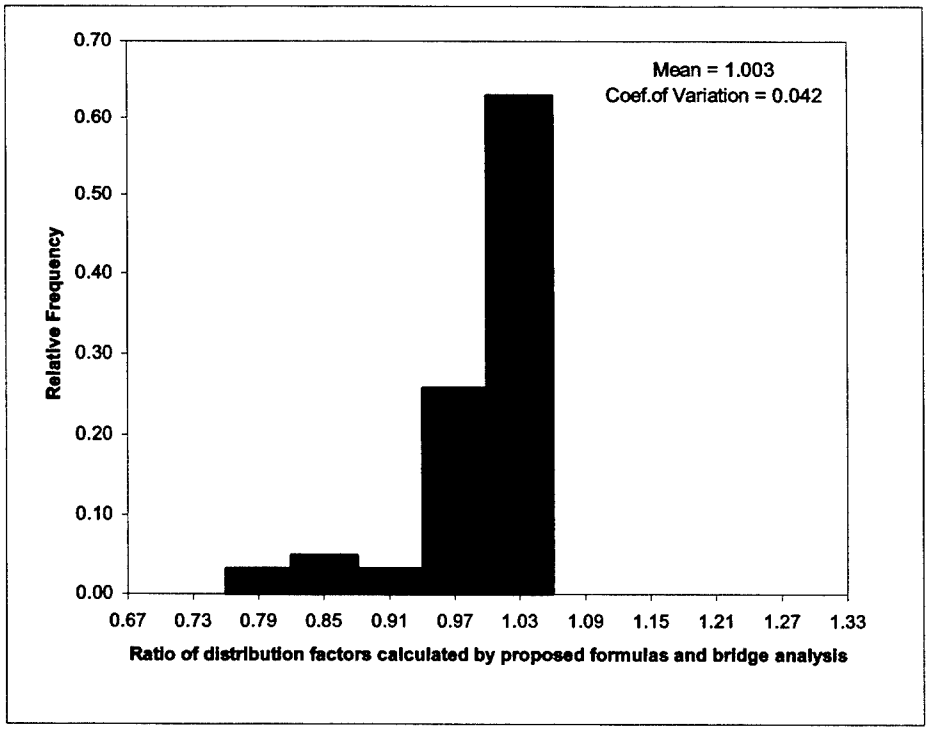


b. Ratio of distribution factors

Figure 45. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams Vehicle, all beam bridges, bending moment in interior girders for single lane

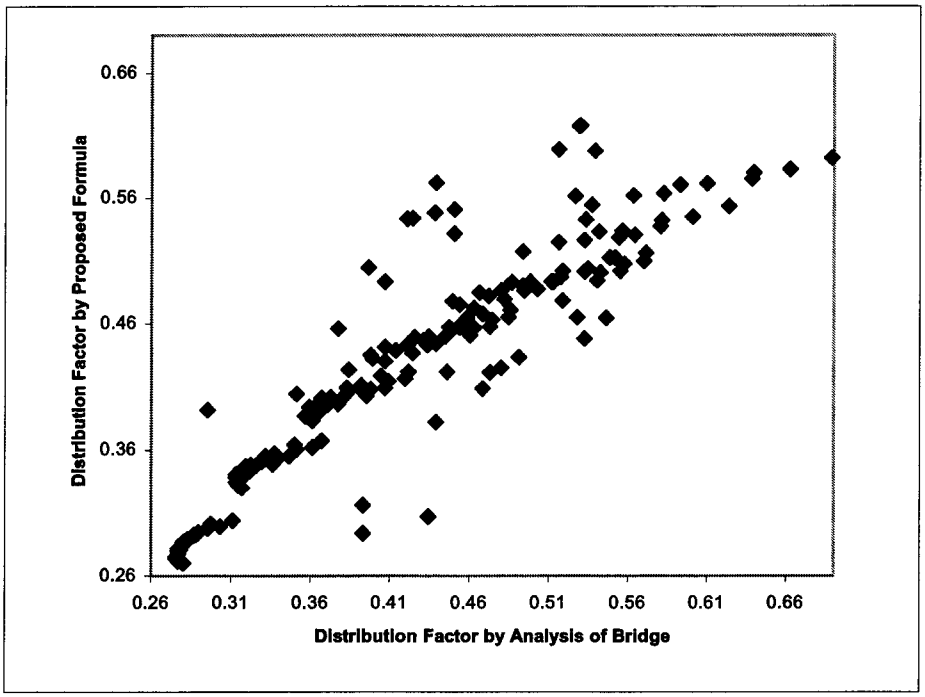


a. Distribution factor

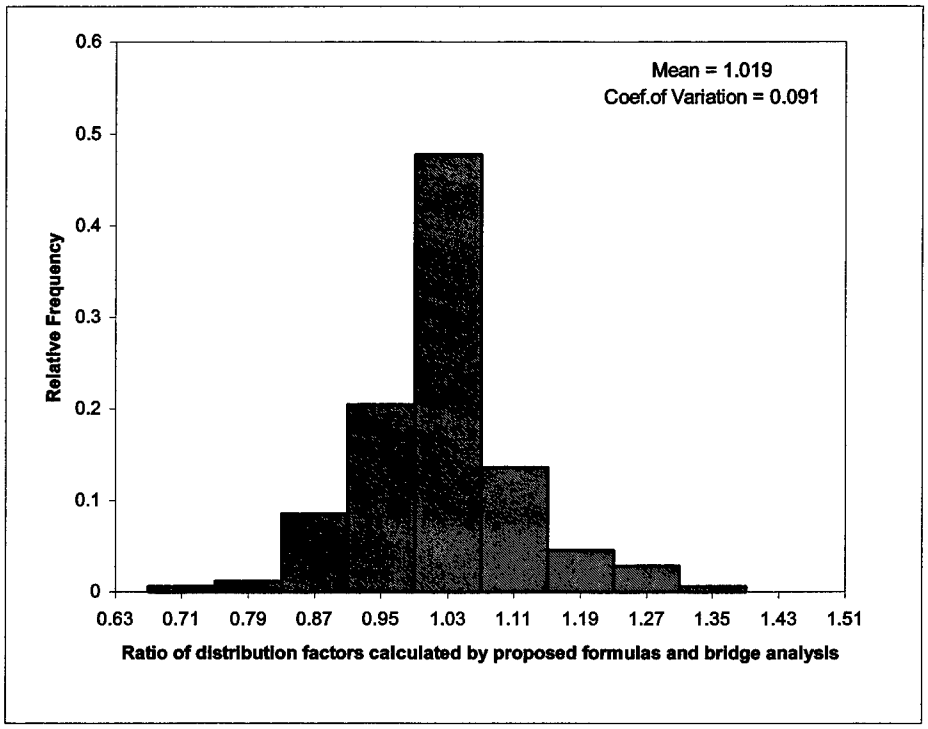


b. Ratio of distribution factors

Figure 46. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams vehicle, steel girder, bending moment in interior girders for single lane

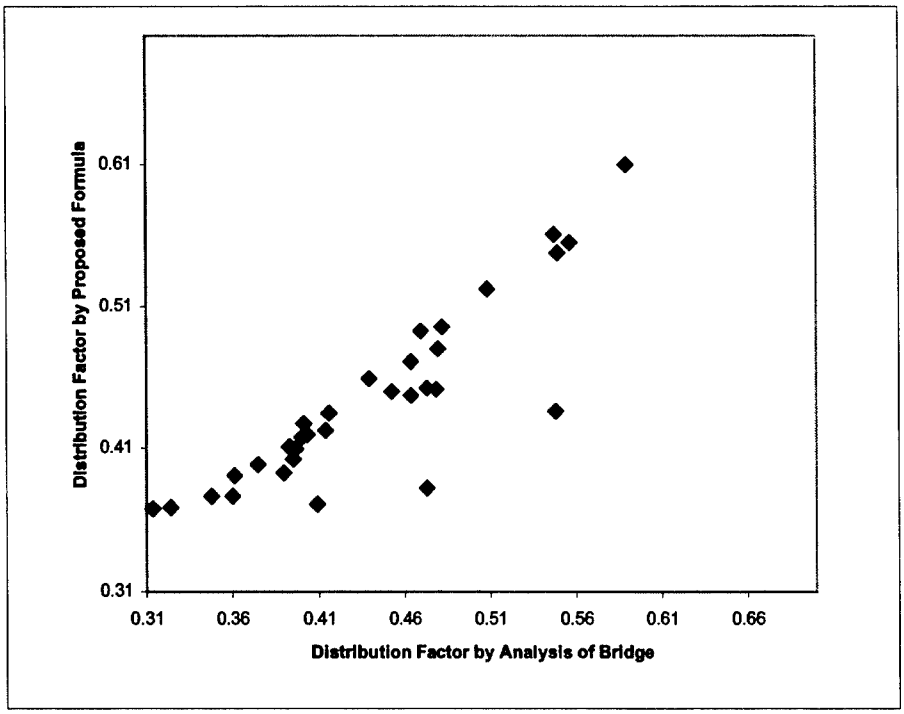


a. Distribution factor

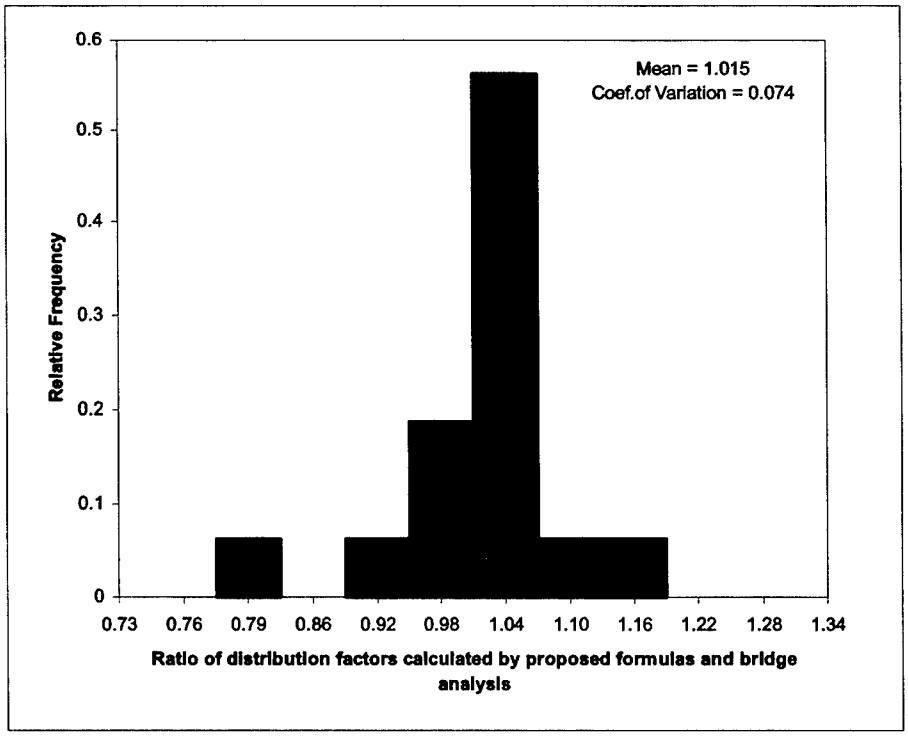


b. Ratio of distribution factors

Figure 47. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams vehicle, prestressed girder, bending moment in interior girders for single lane

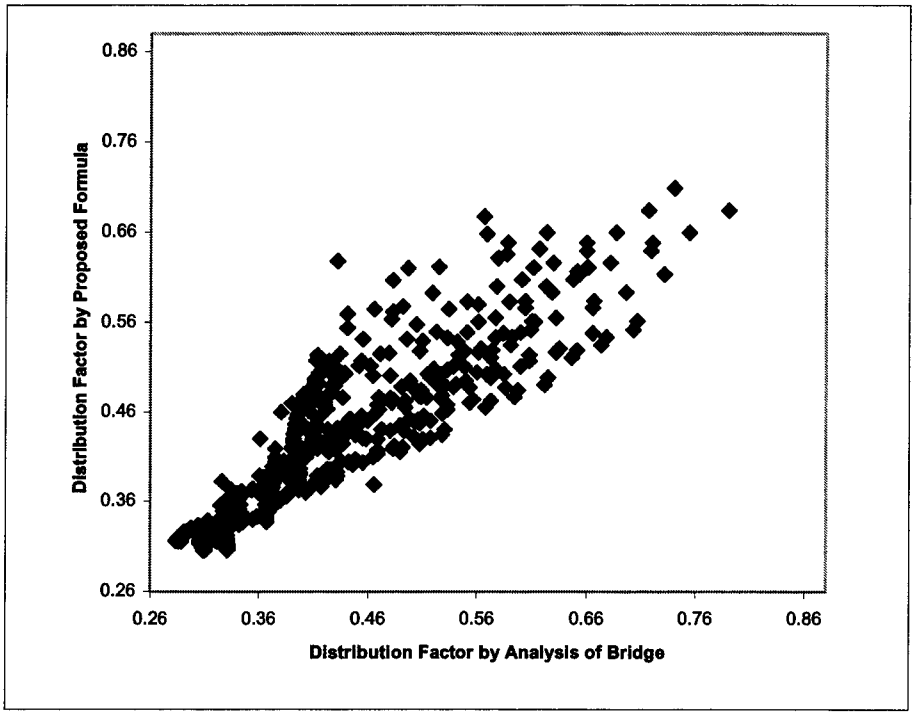


a. Distribution factor

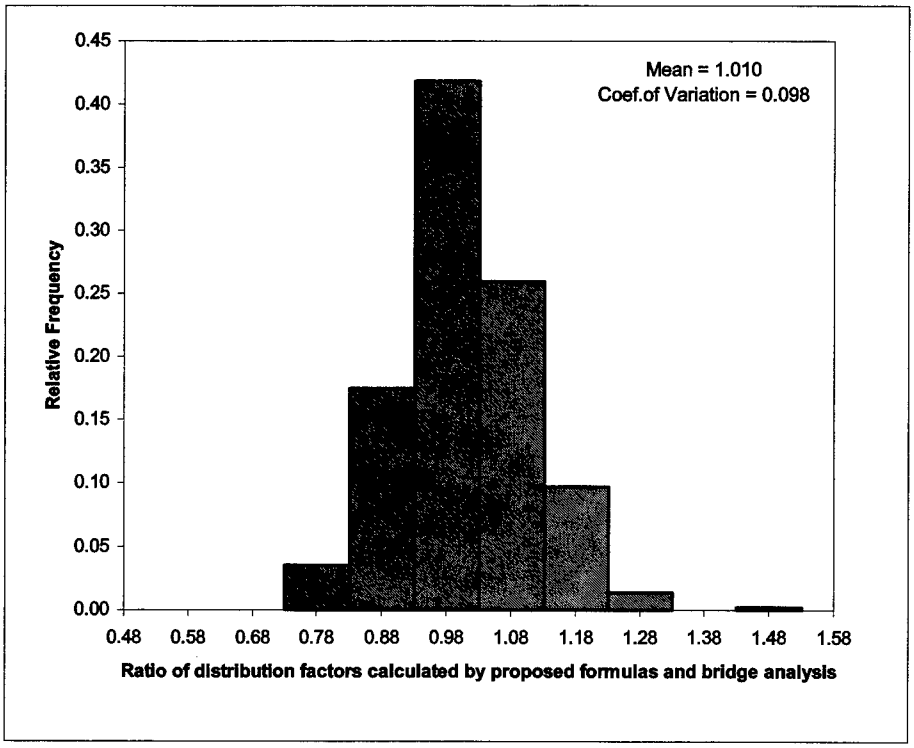


b. Ratio of distribution factors

Figure 48. Comparison of distribution factors calculated by proposed formulas and bridge analysis for Abrams vehicle, concrete T-beam, bending moment in interior girders for single lane

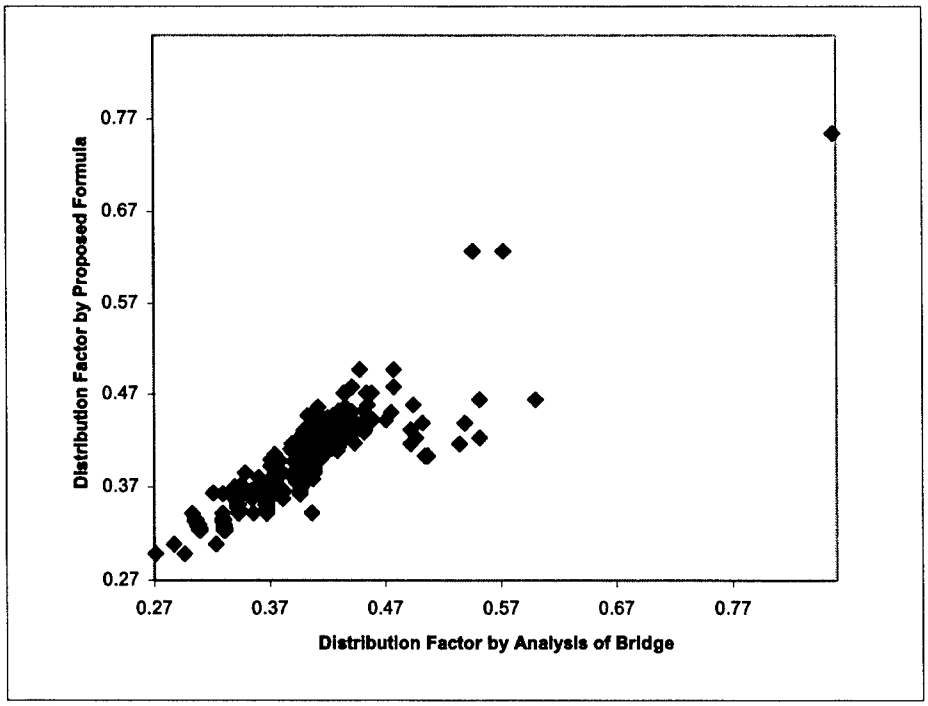


a. Distribution factor

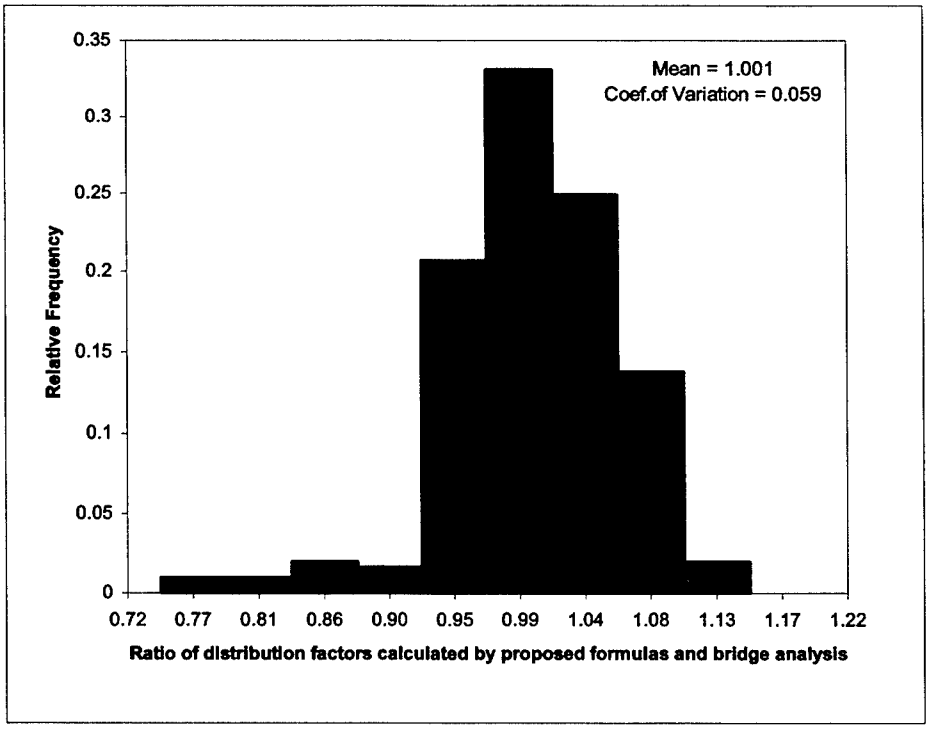


b. Ratio of distribution factors

Figure 49. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, all beam bridges, bending moment in interior girders for single lane

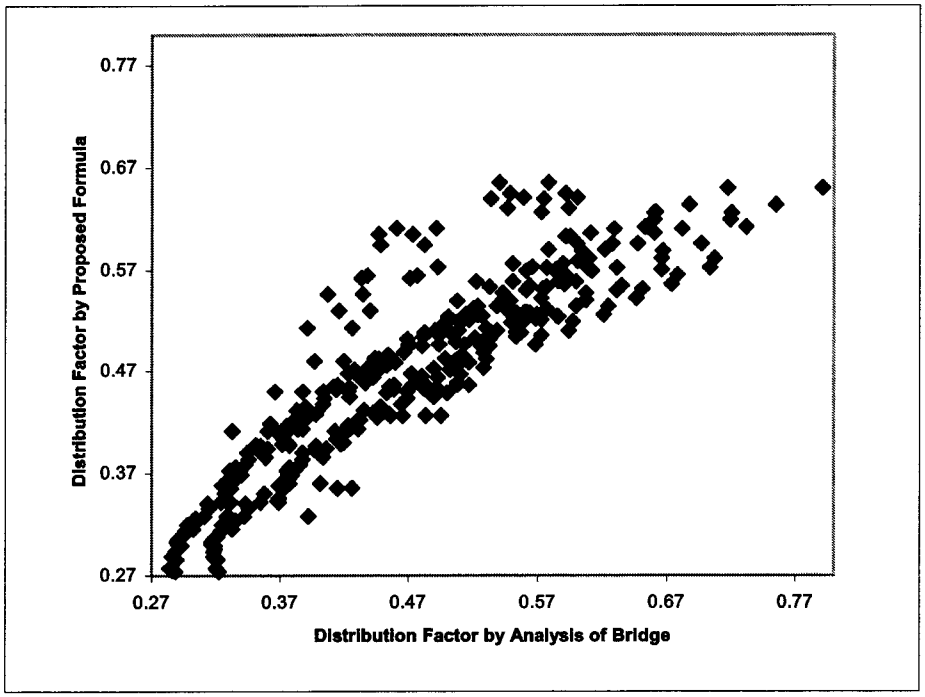


a. Distribution factor

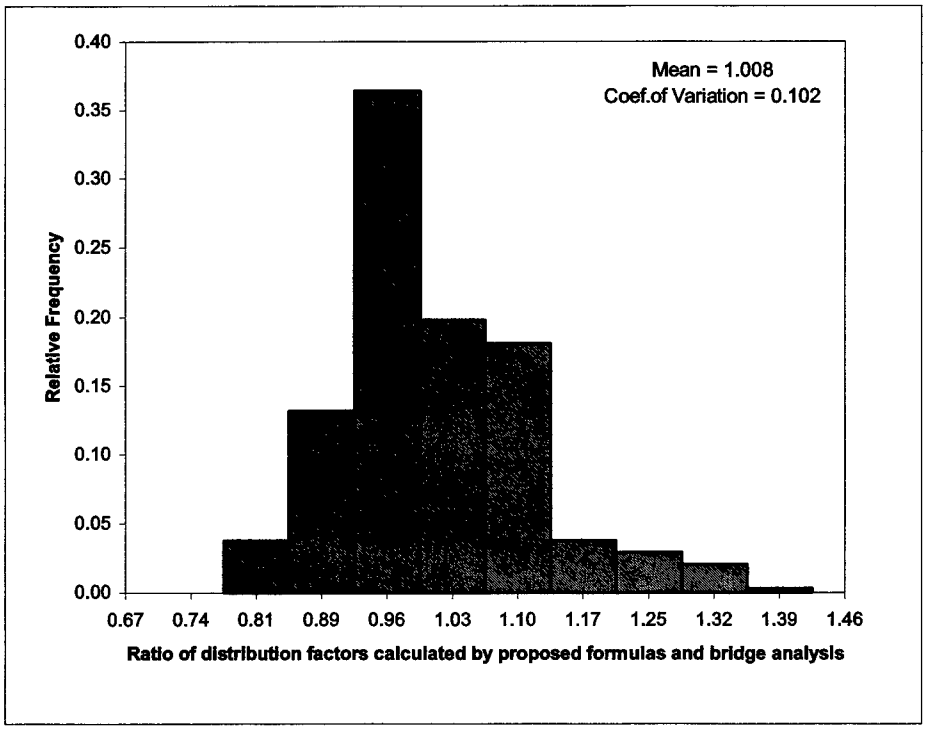


b. Ratio of distribution factors

Figure 50. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, steel girder, bending moment in interior girders for single lane

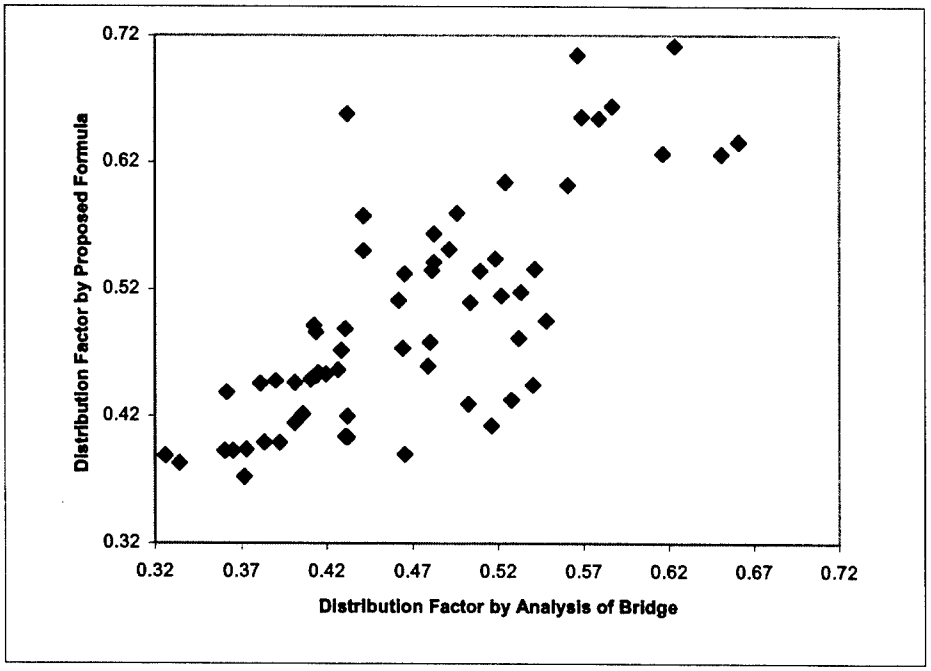


a. Distribution factor

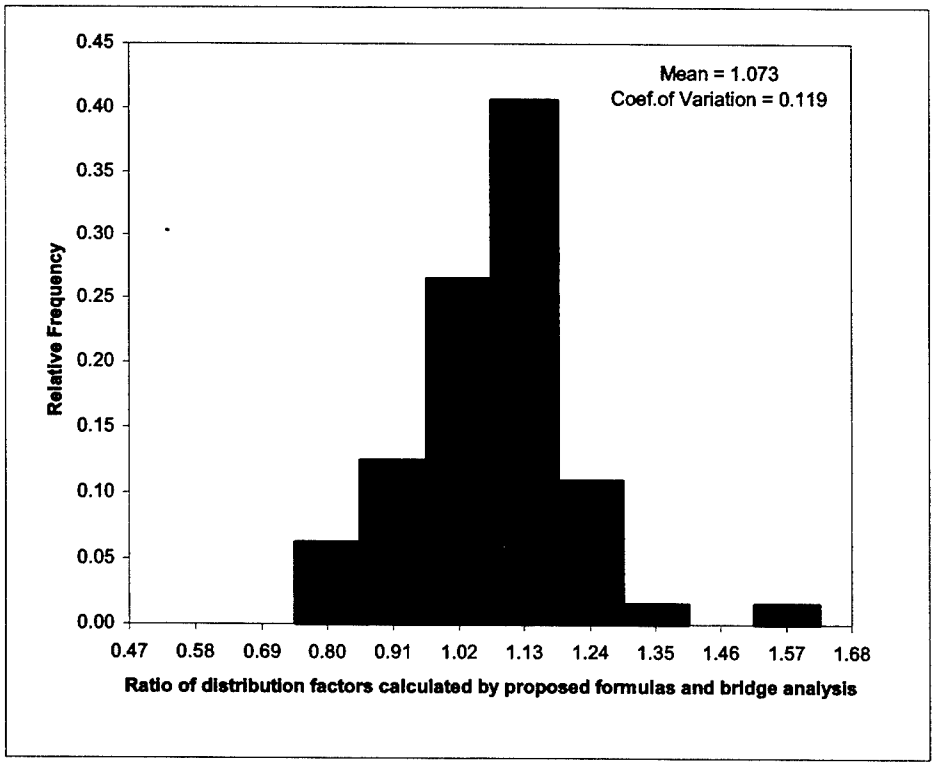


b. Ratio of distribution factors

Figure 51. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, prestressed girder, bending moment in interior girders for single lane

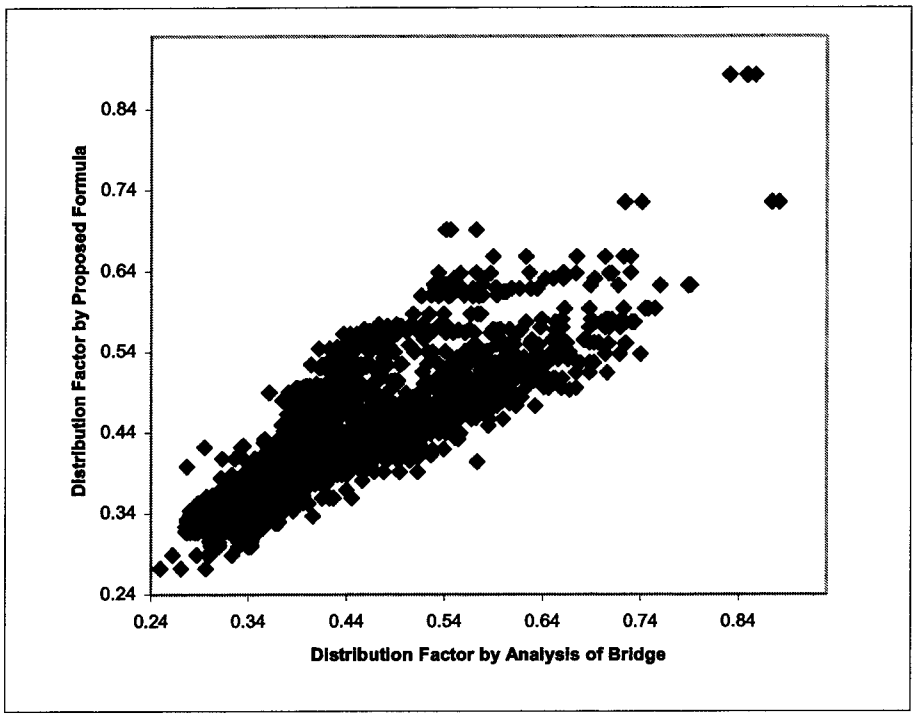


a. Distribution factor

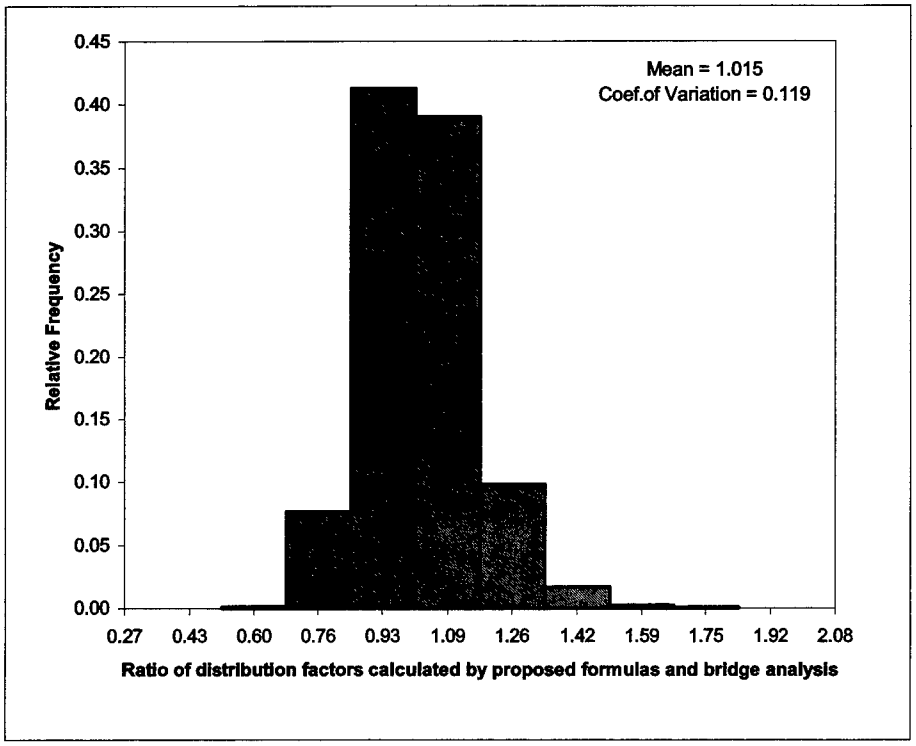


b. Ratio of distribution factors

Figure 52. Comparison of distribution factors calculated by proposed formulas and bridge analysis for M113 and Bradley vehicles, concrete T-beam, bending moment in interior girders for single lane

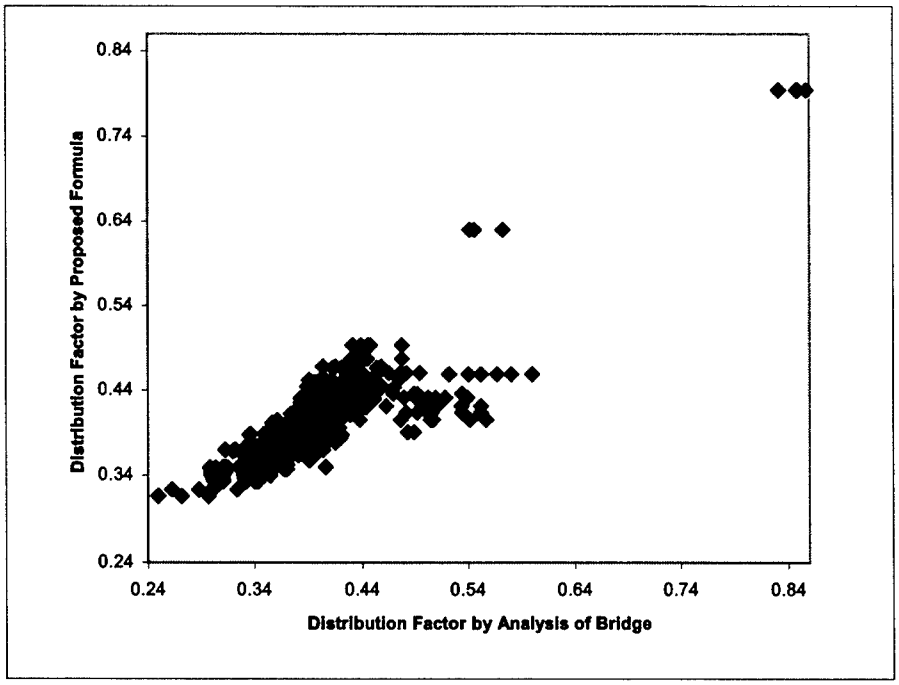


a. Distribution factor

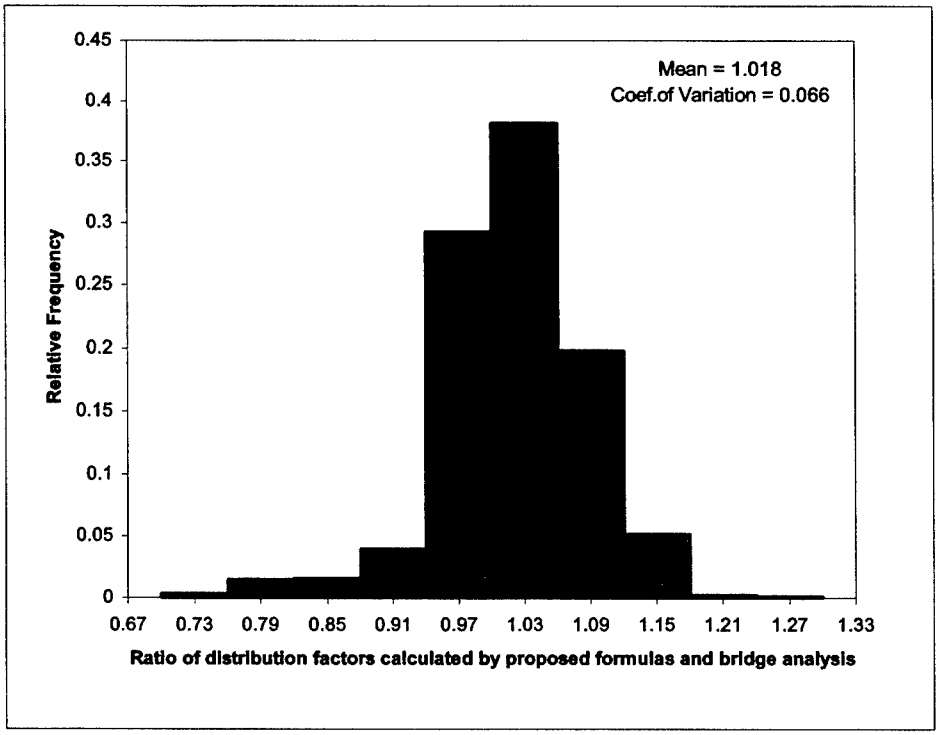


b. Ratio of distribution factors

Figure 53. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in interior girders for single lane

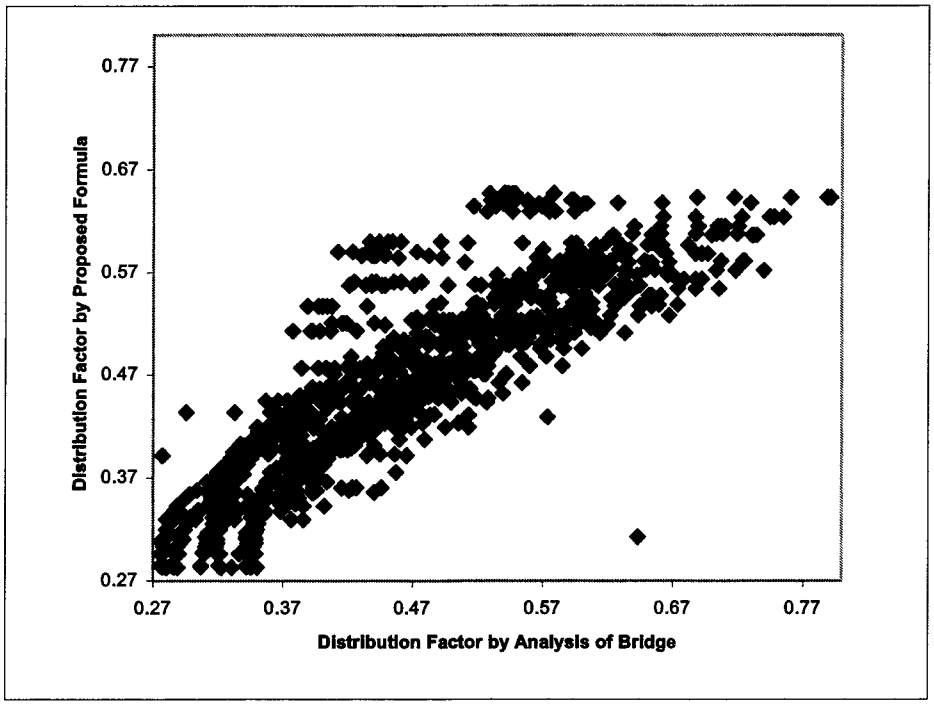


a. Distribution factor

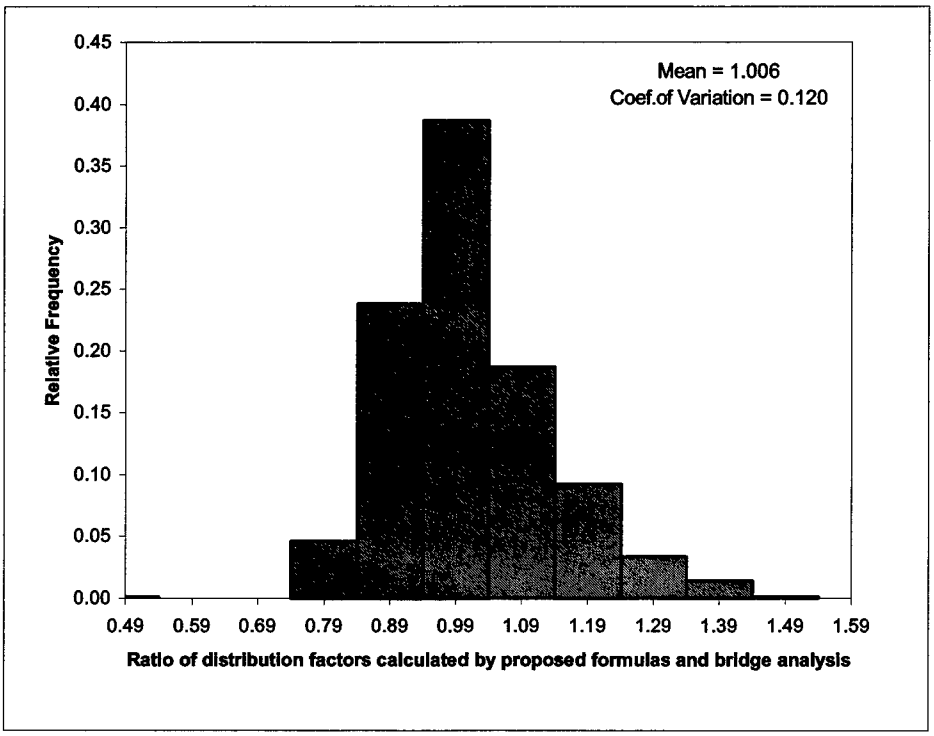


b. Ratio of distribution factors

Figure 54. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in interior girders for single lane

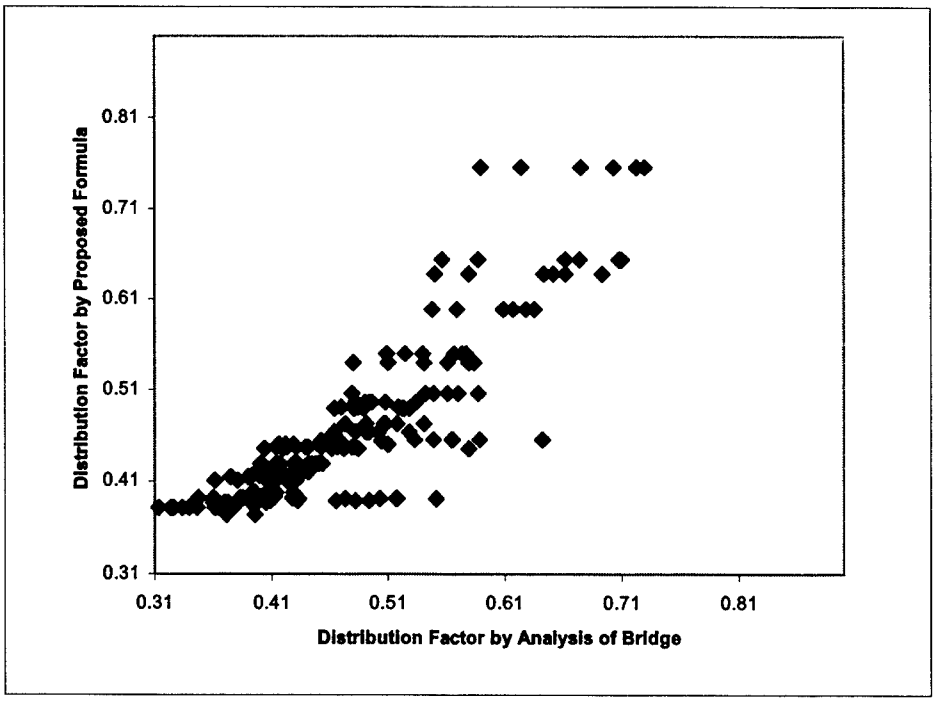


a. Distribution factor

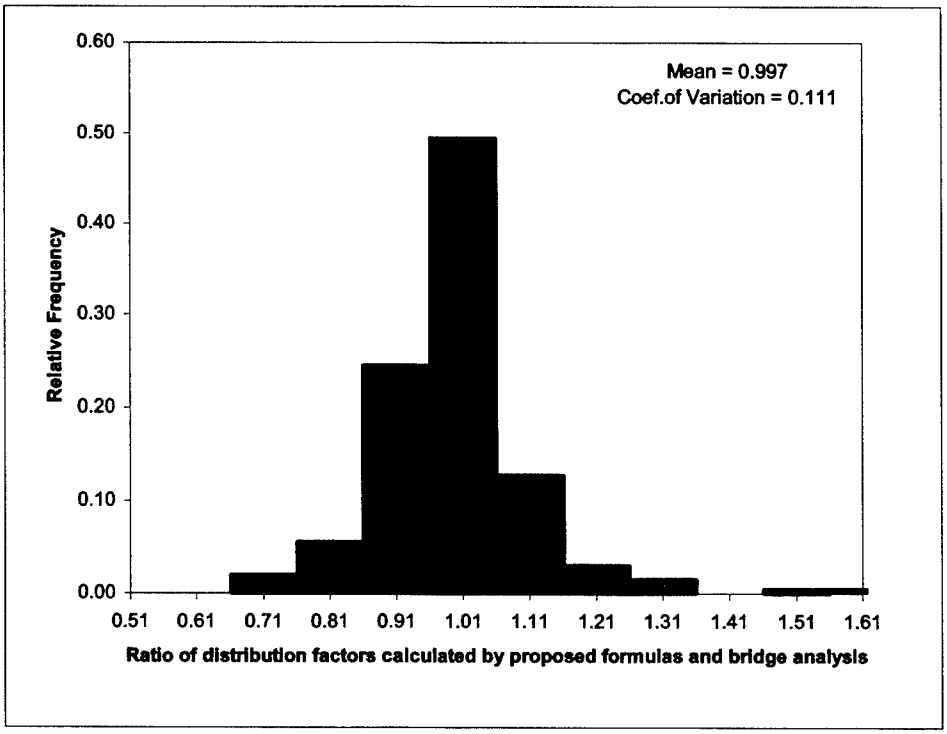


b. Ratio of distribution factors

Figure 55. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in interior girders for single lane

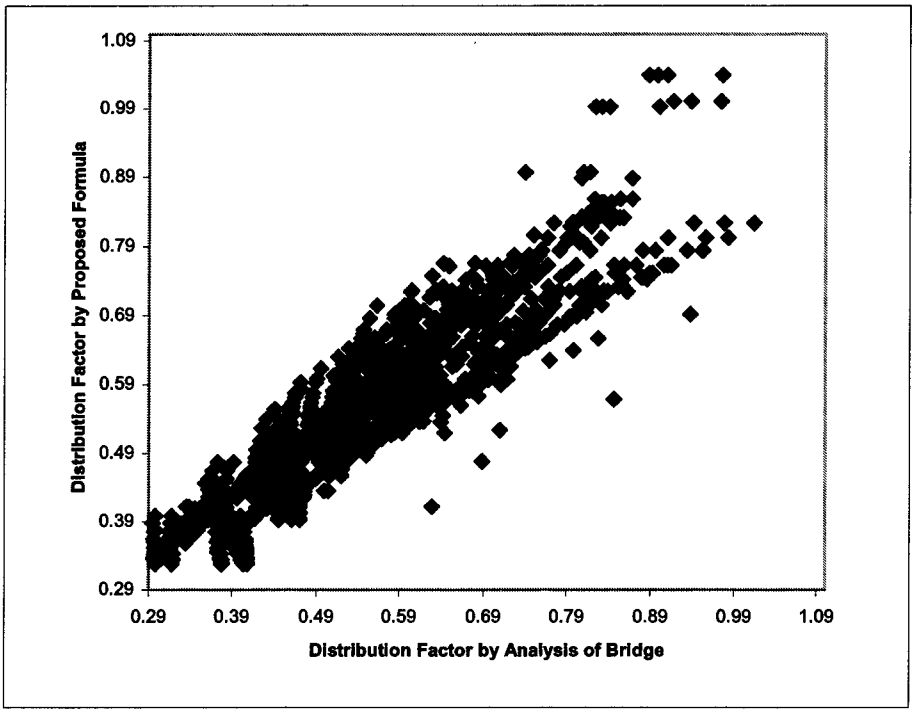


a. Distribution factor

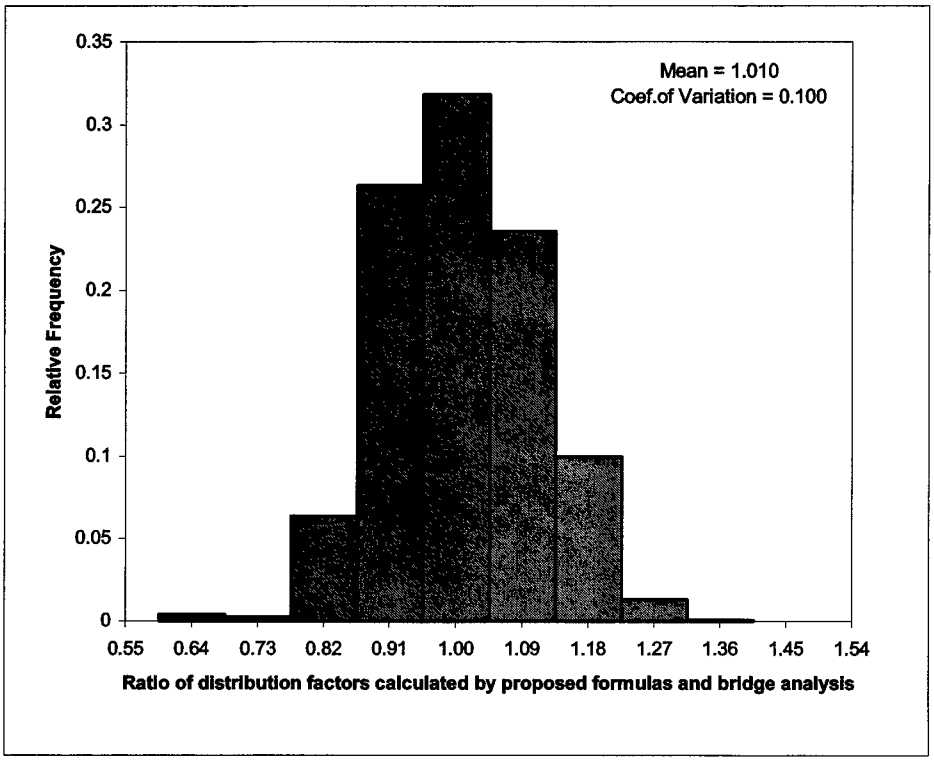


b. Ratio of distribution factors

Figure 56. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in interior girders for single lane

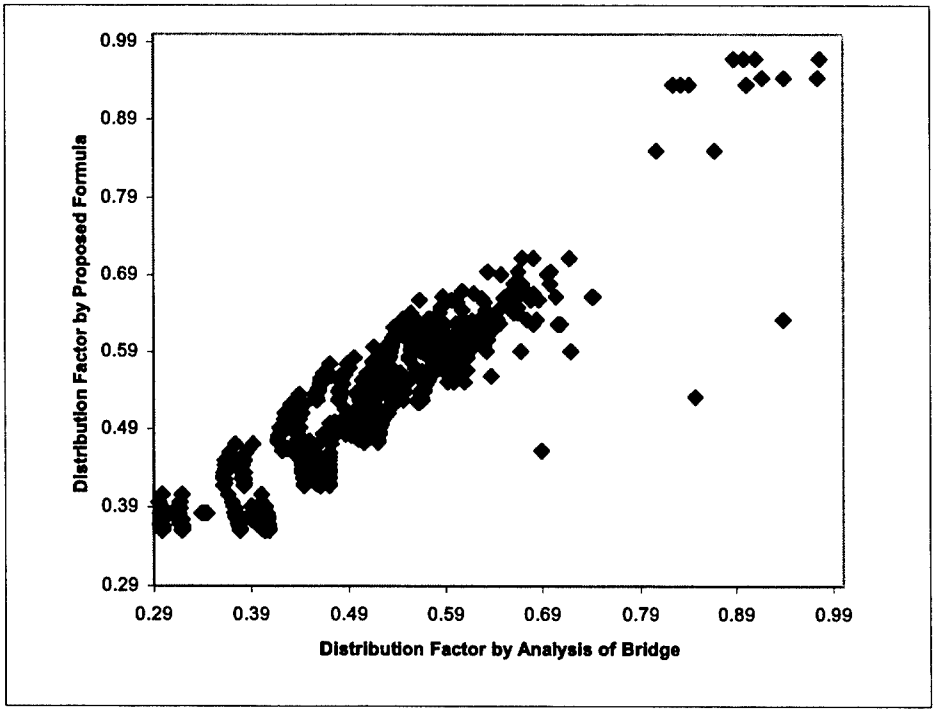


a. Distribution factor

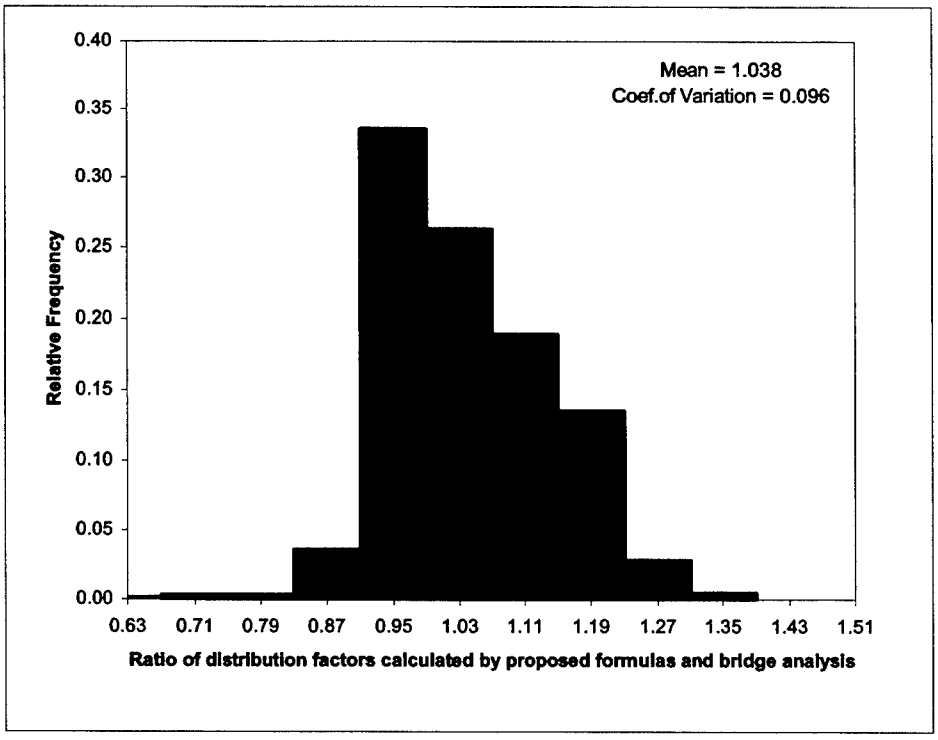


b. Ratio of distribution factors

Figure 57. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in interior girders for multiple lane

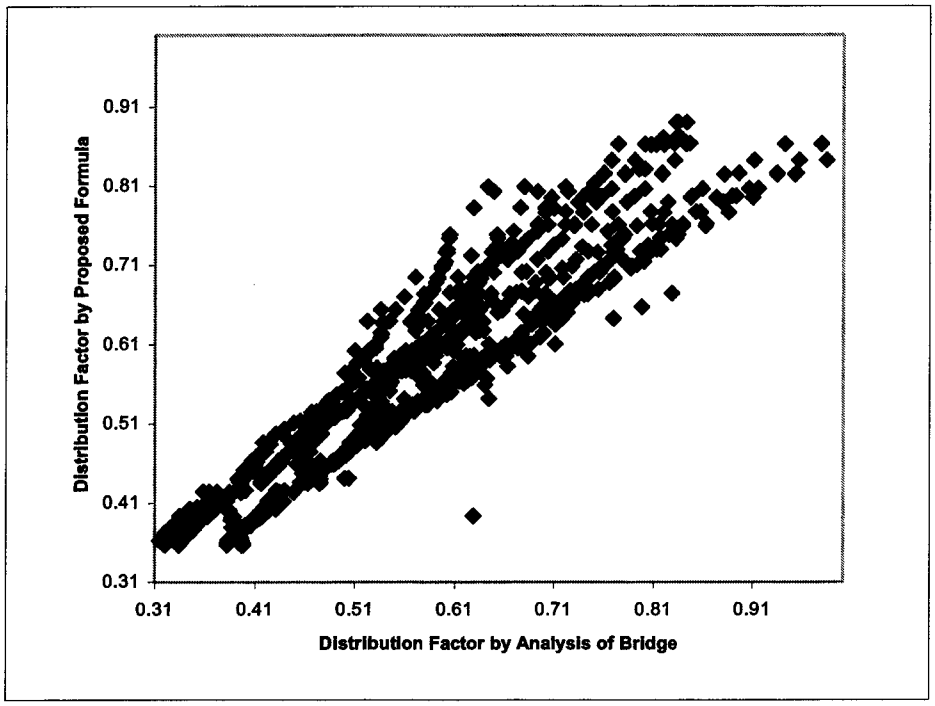


a. Distribution factor

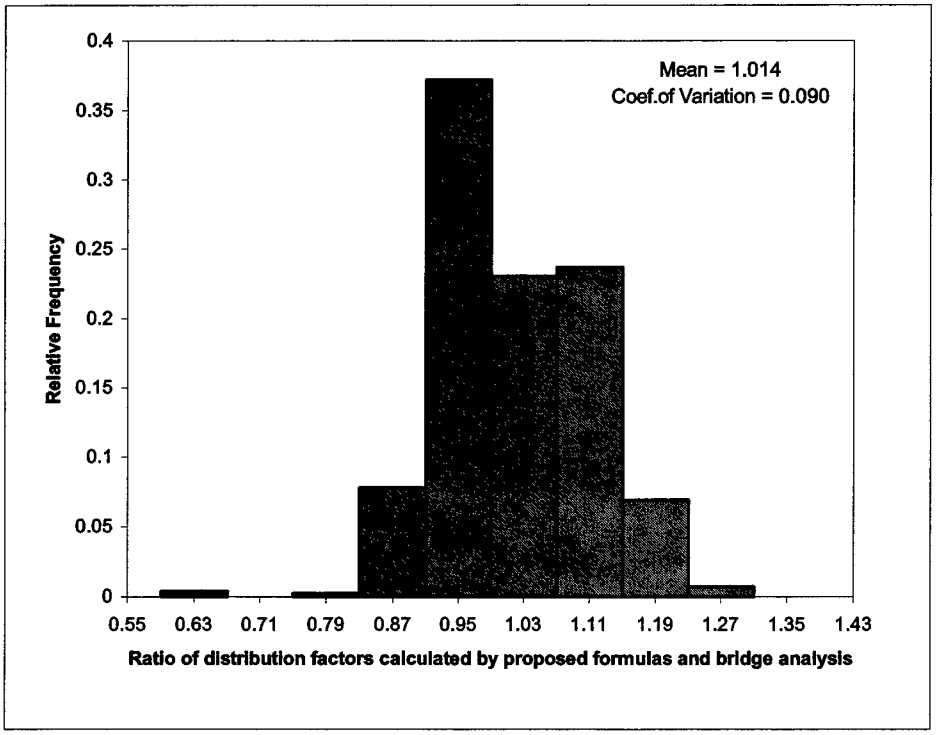


b. Ratio of distribution factors

Figure 58. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in interior girders for multiple lane

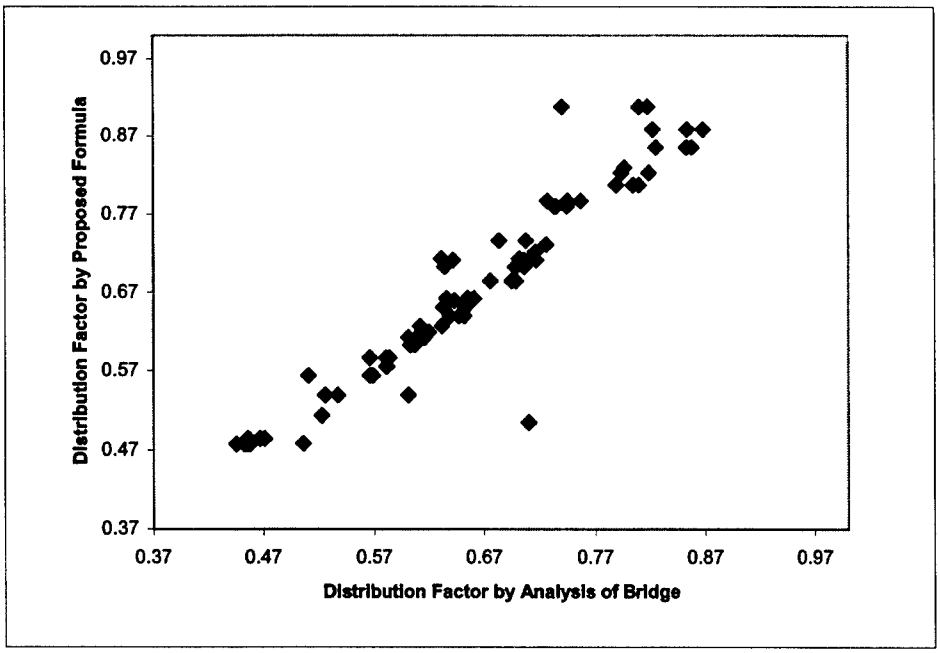


a. Distribution factor

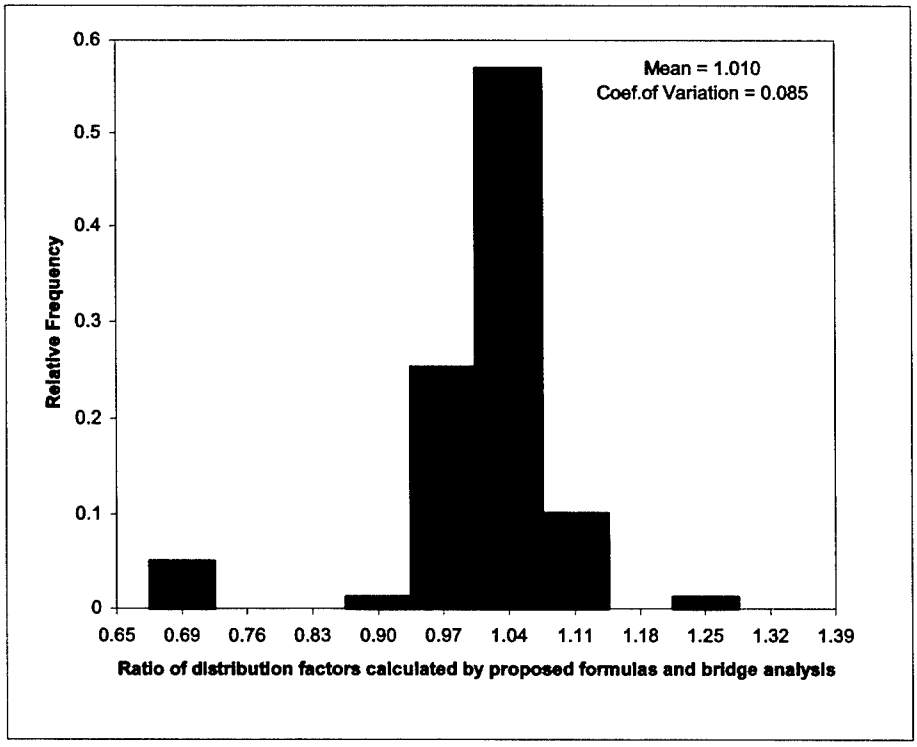


b. Ratio of distribution factors

Figure 59. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in interior girders for multiple lane

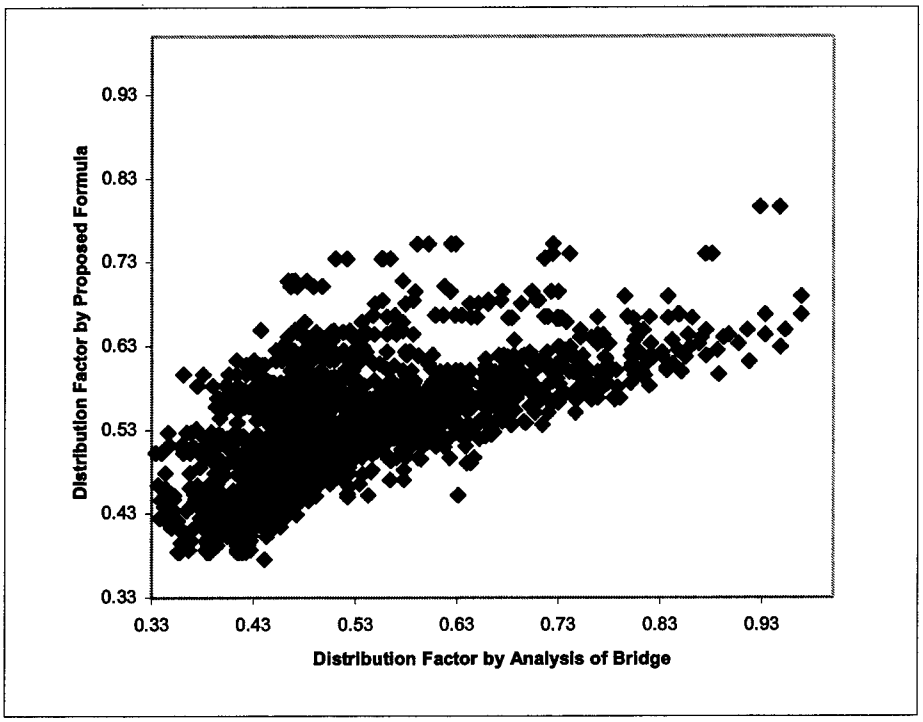


a. Distribution factor

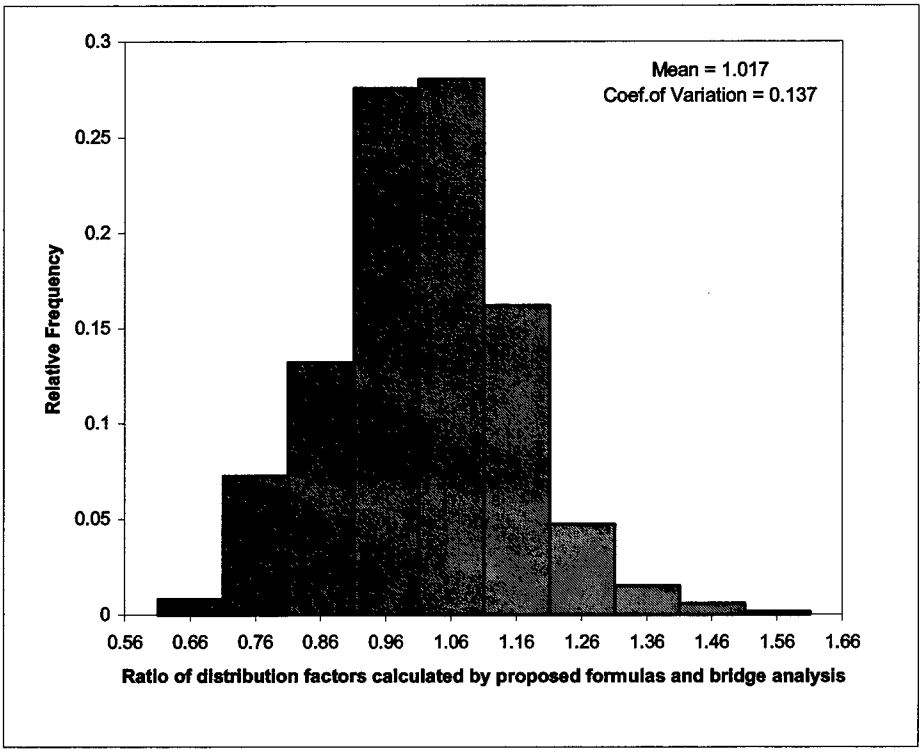


b. Ratio of distribution factors

Figure 60. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in interior girders for multiple lane

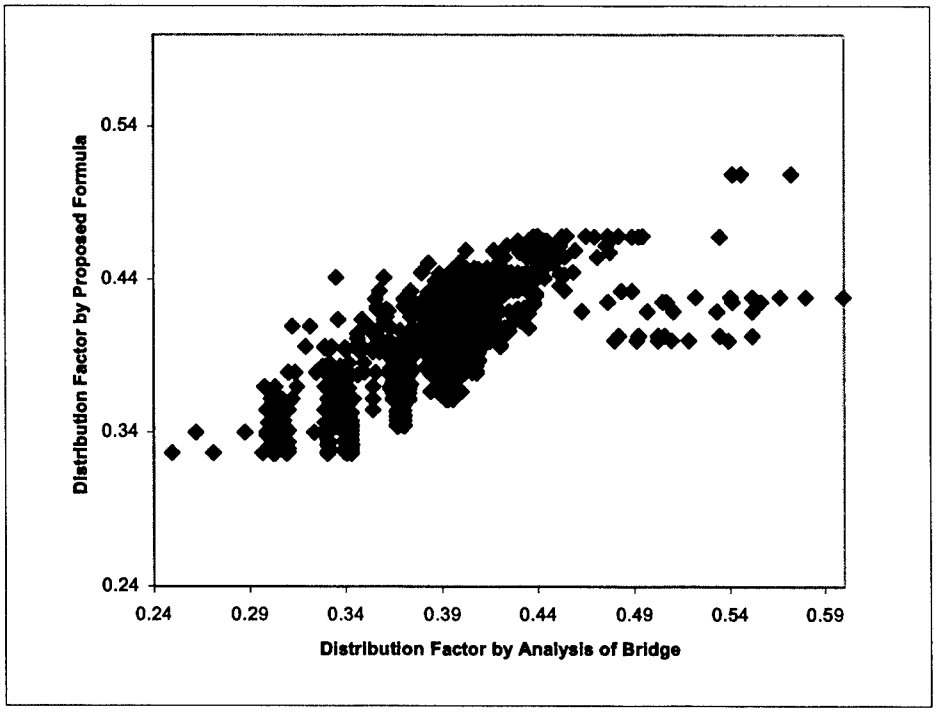


a. Distribution factor

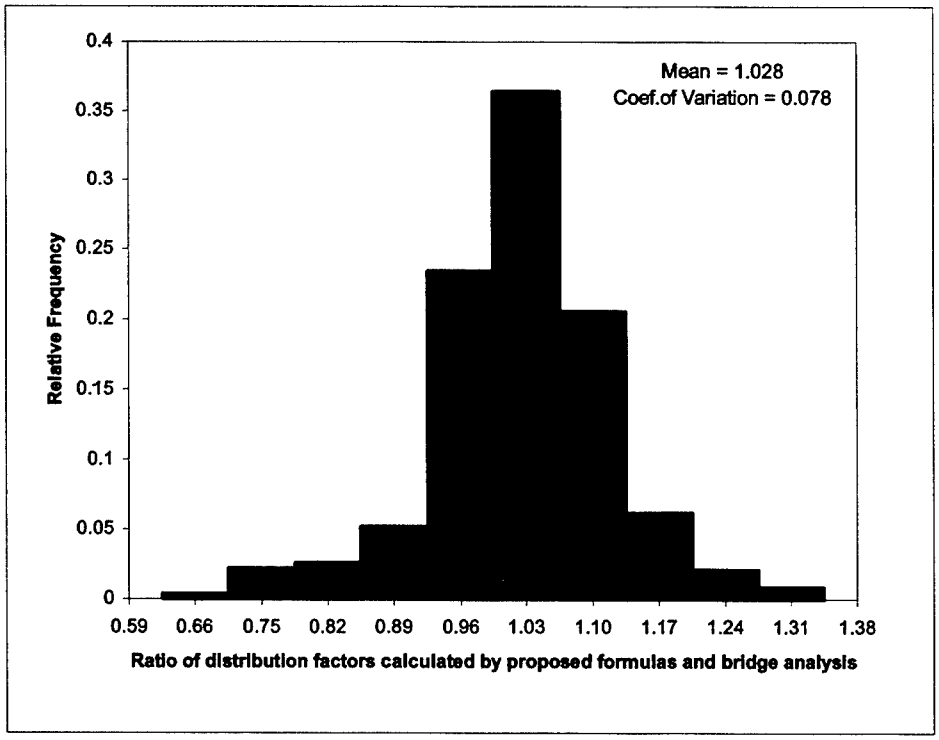


b. Ratio of distribution factors

Figure 61. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in interior girders for single lane

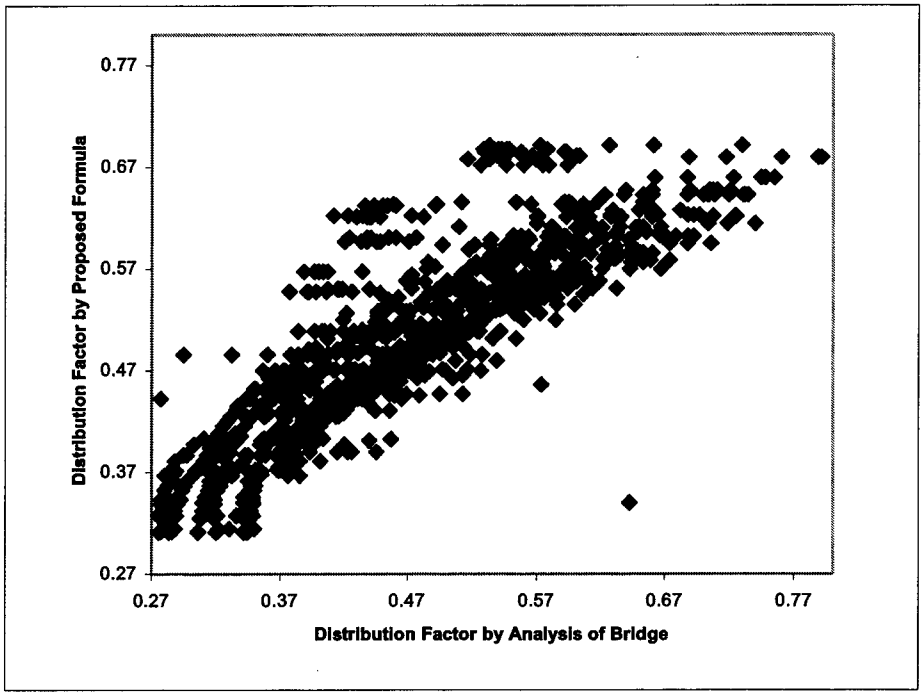


a. Distribution factor

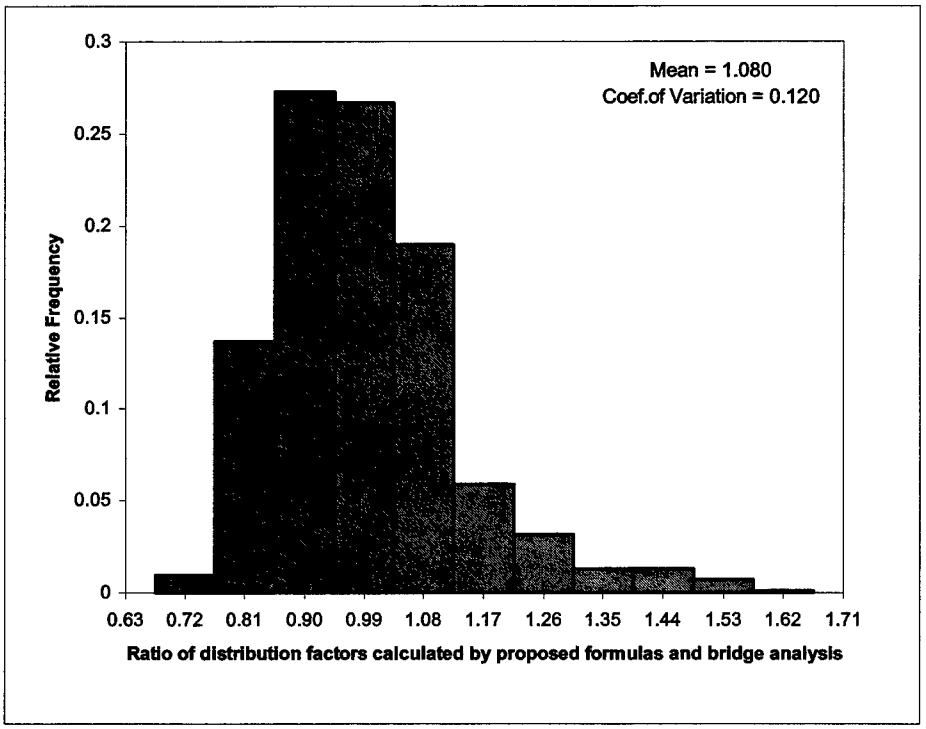


b. Ratio of distribution factors

Figure 62. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in interior girders for single lane

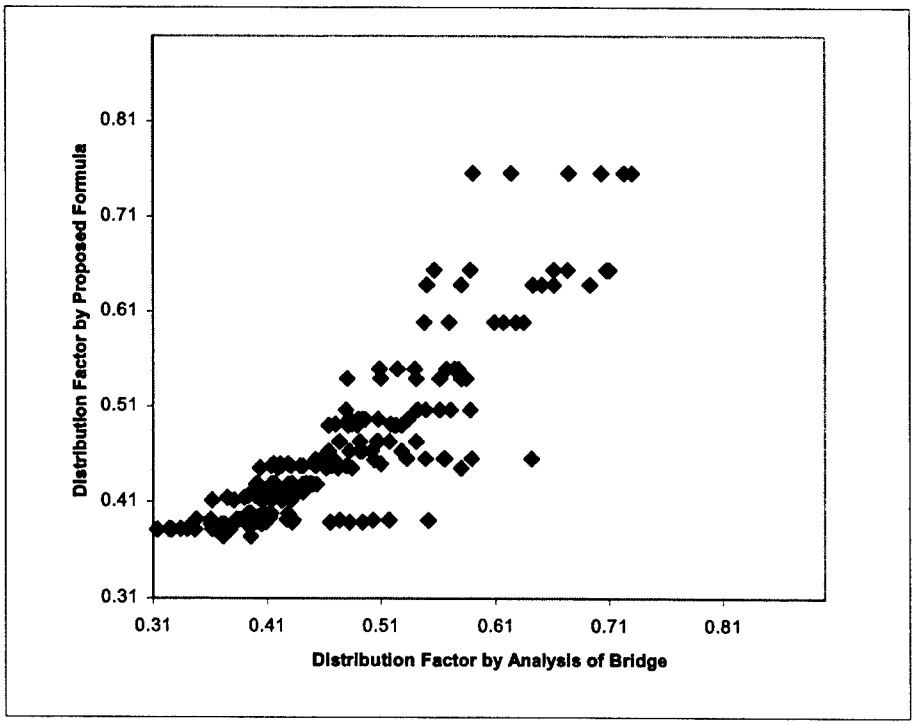


a. Distribution factor

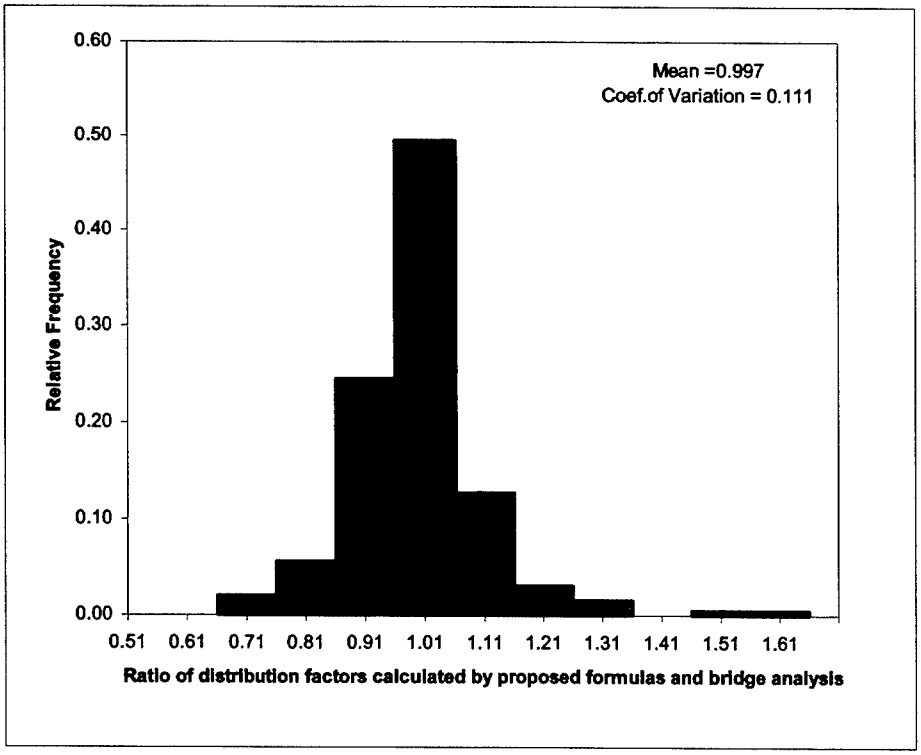


b. Ratio of distribution factors

Figure 63. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, shear in interior girders for single lane

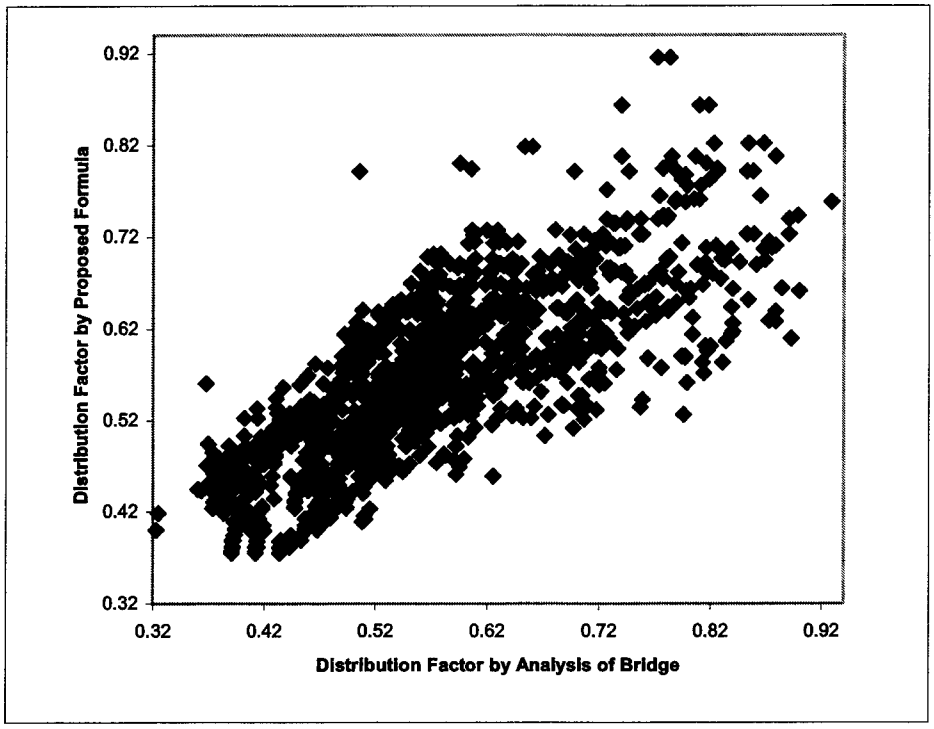


a. Distribution factor

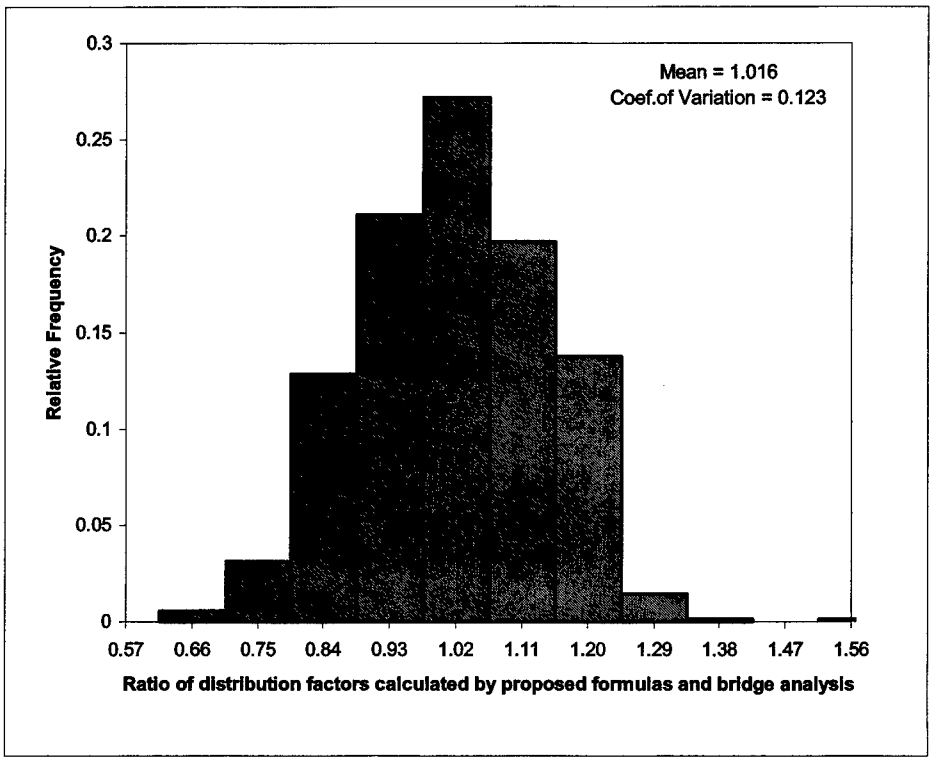


b. Ratio of distribution factors

Figure 64. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in interior girders for single lane

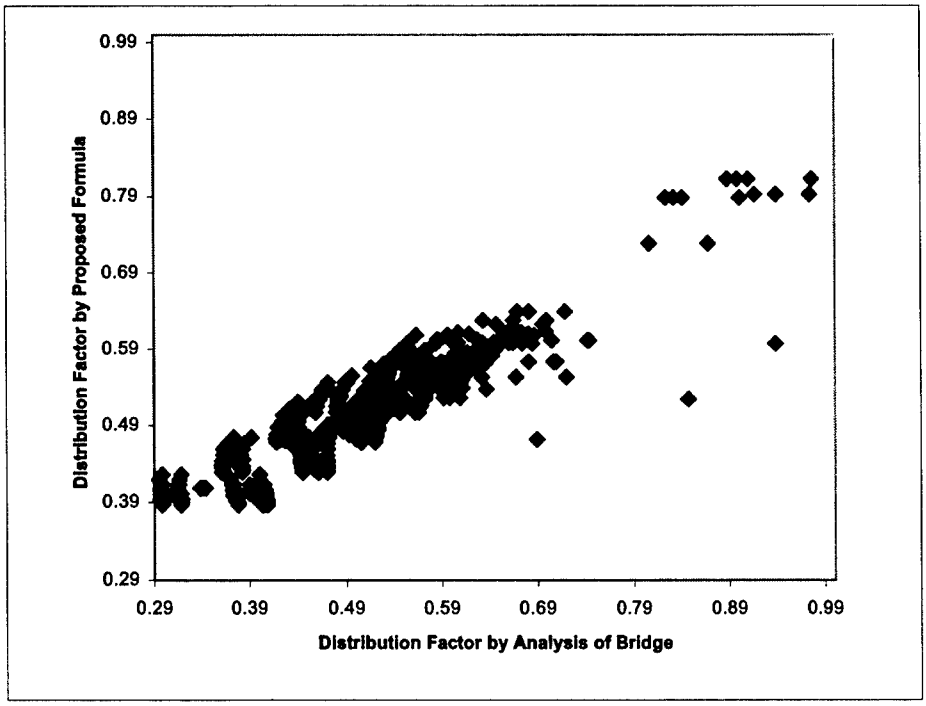


a. Distribution factor

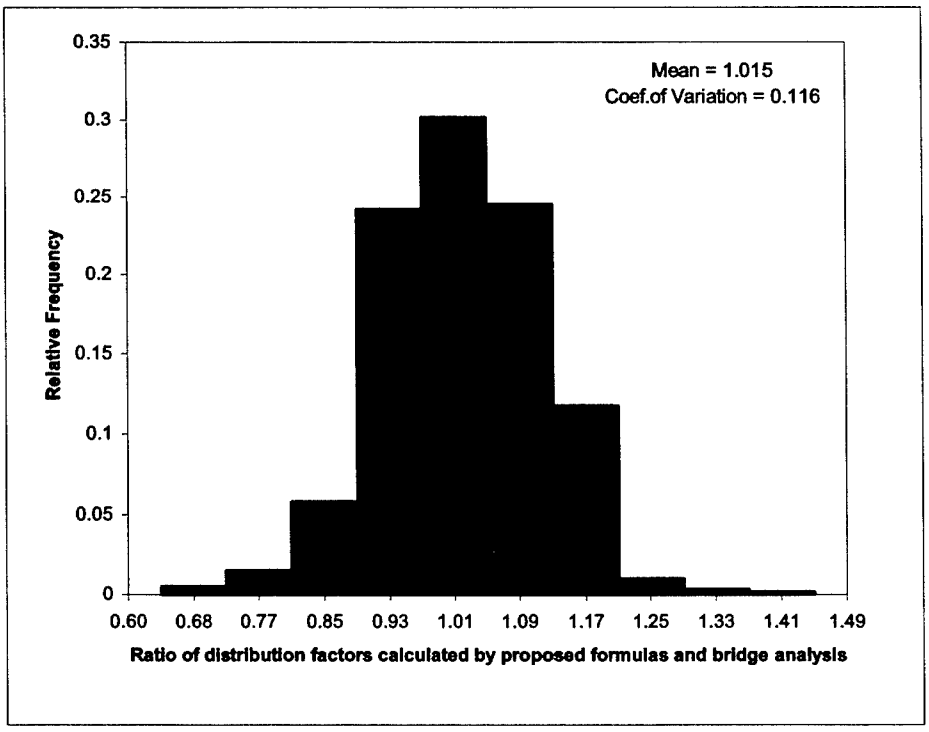


b. Ratio of distribution factors

Figure 65. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in interior girders for multiple lane

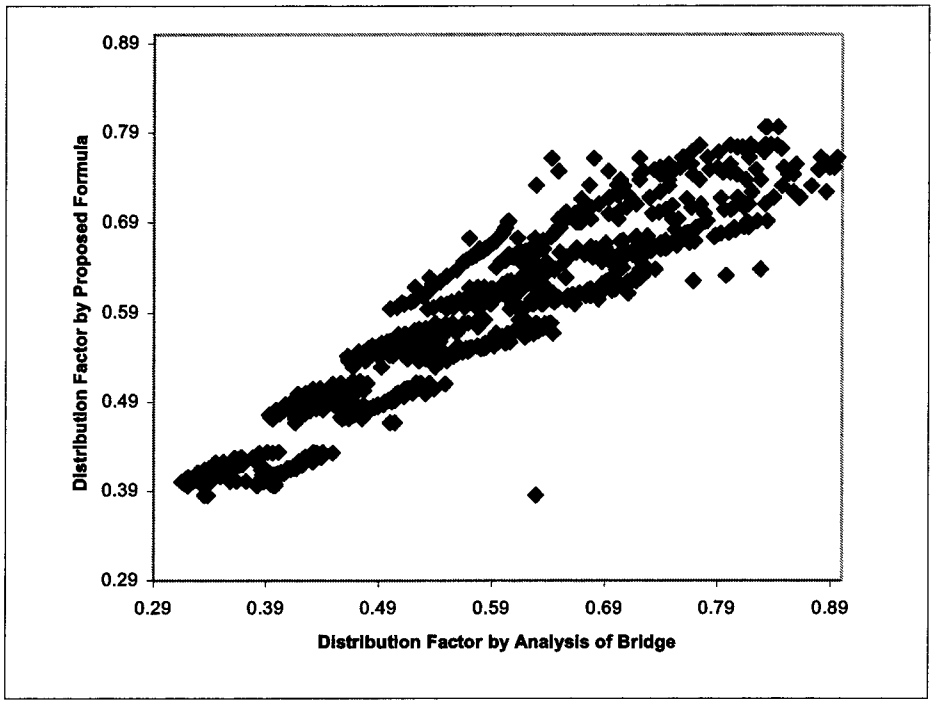


a. Distribution factor

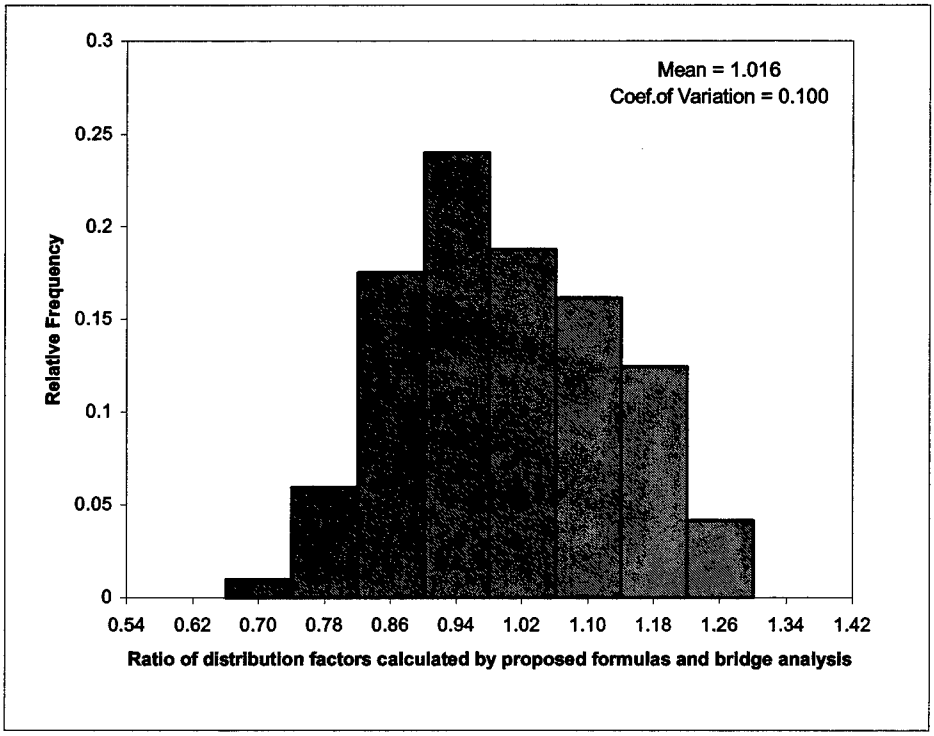


b. Ratio of distribution factors

Figure 66. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in interior girders for multiple lane

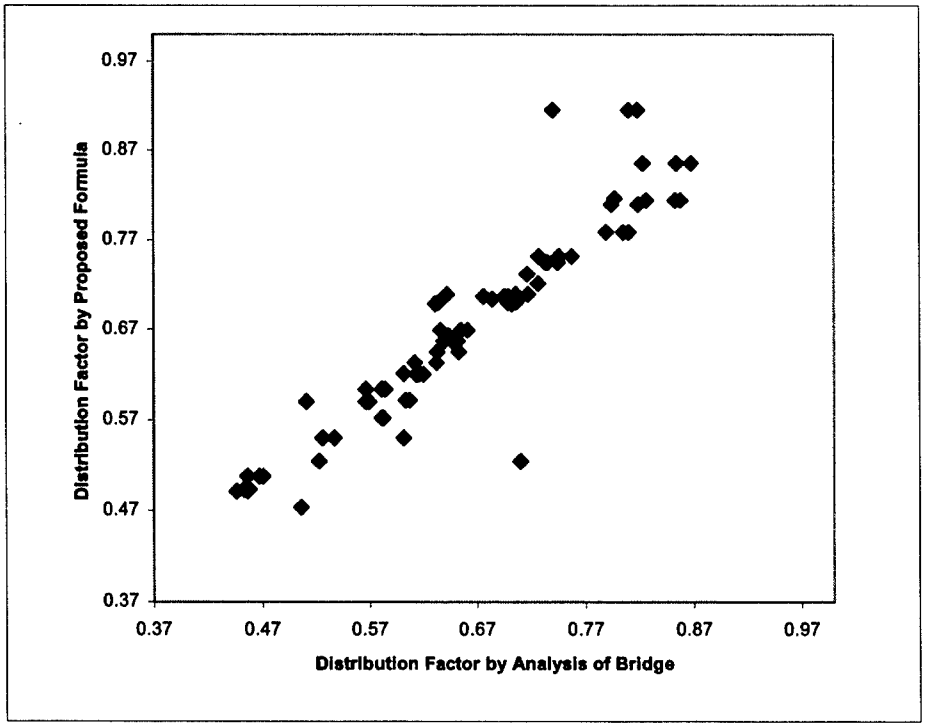


a. Distribution factor

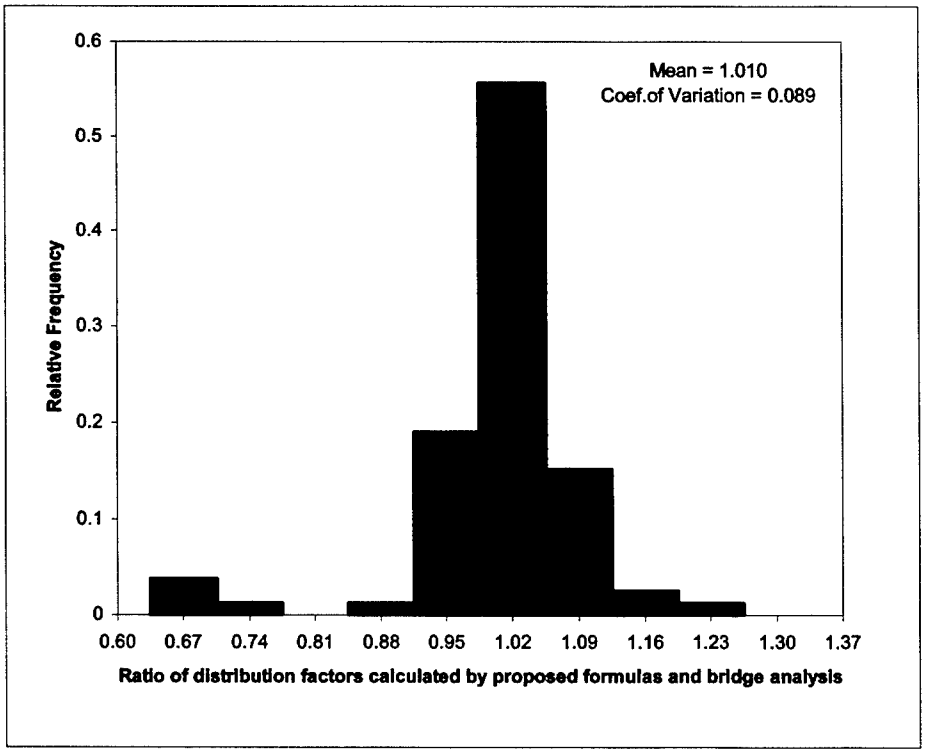


b. Ratio of distribution factors

Figure 67. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, shear in interior girders for multiple lane

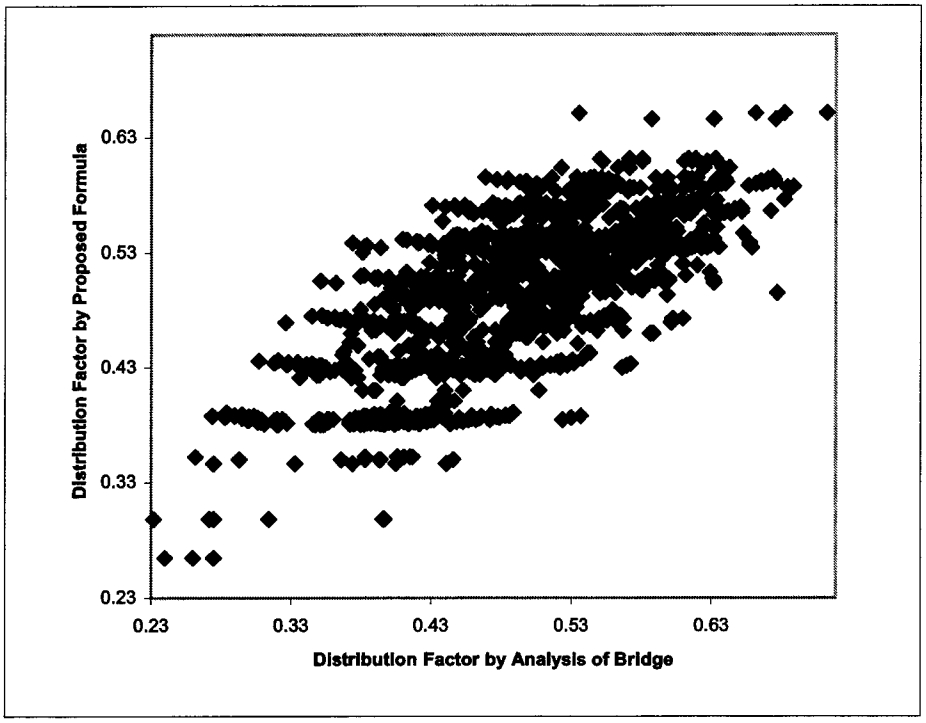


a. Distribution factor

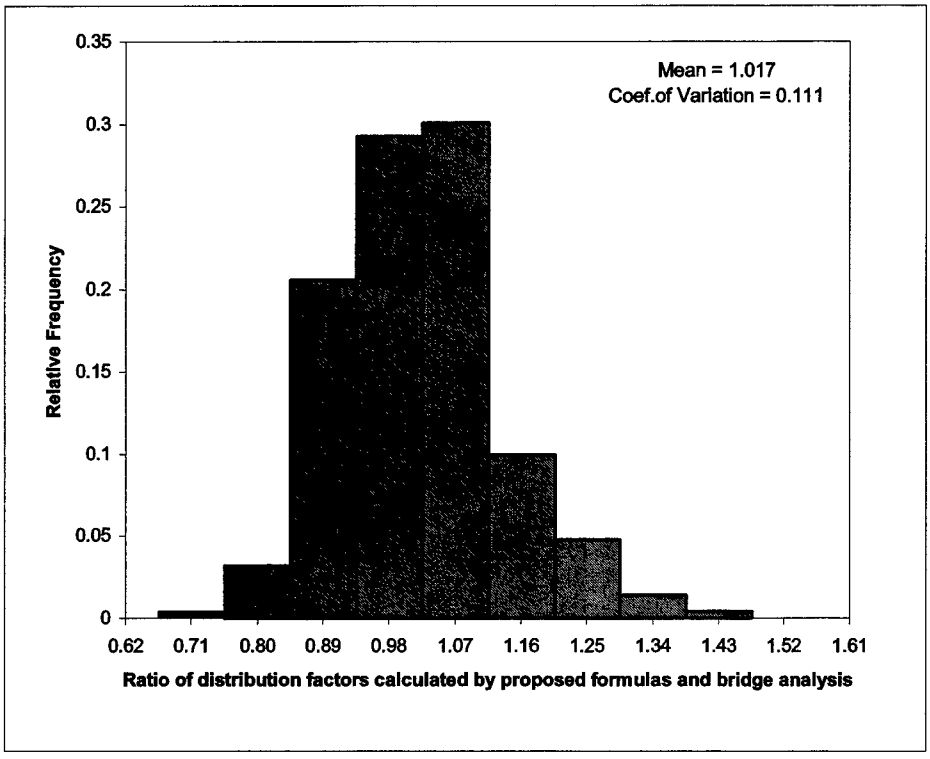


b. Ratio of distribution factors

Figure 68. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in interior girders for multiple lane

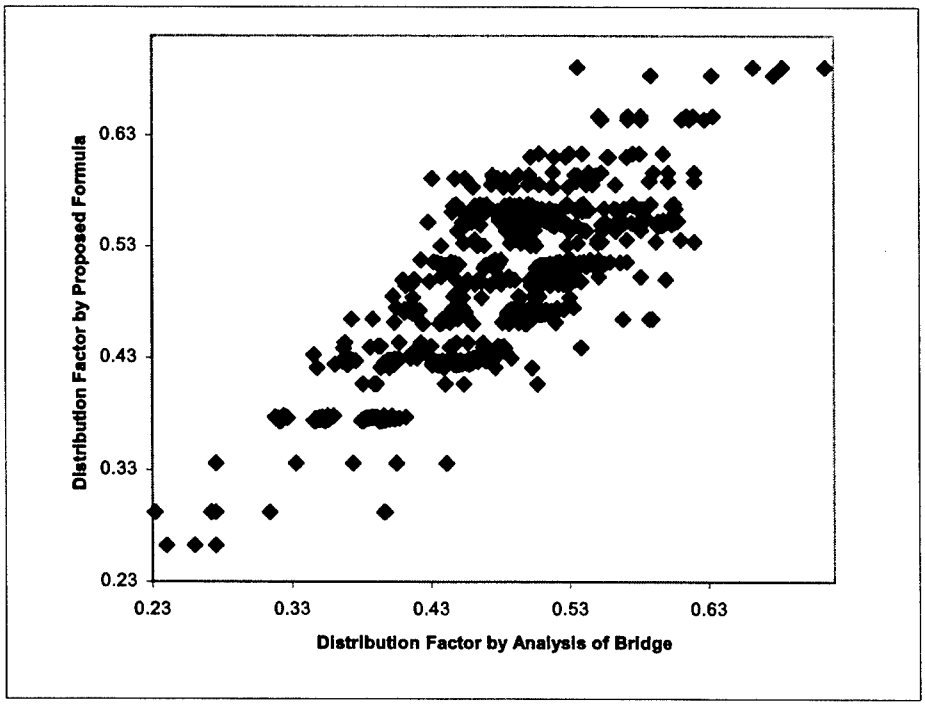


a. Distribution factor

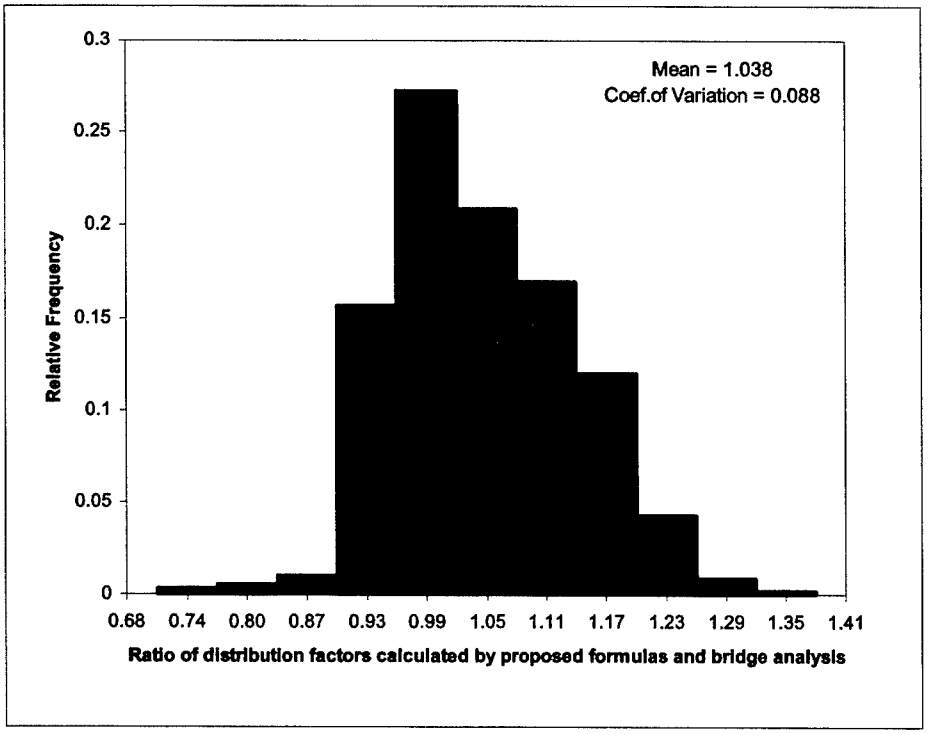


b. Ratio of distribution factors

Figure 69. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in exterior girders for single lane

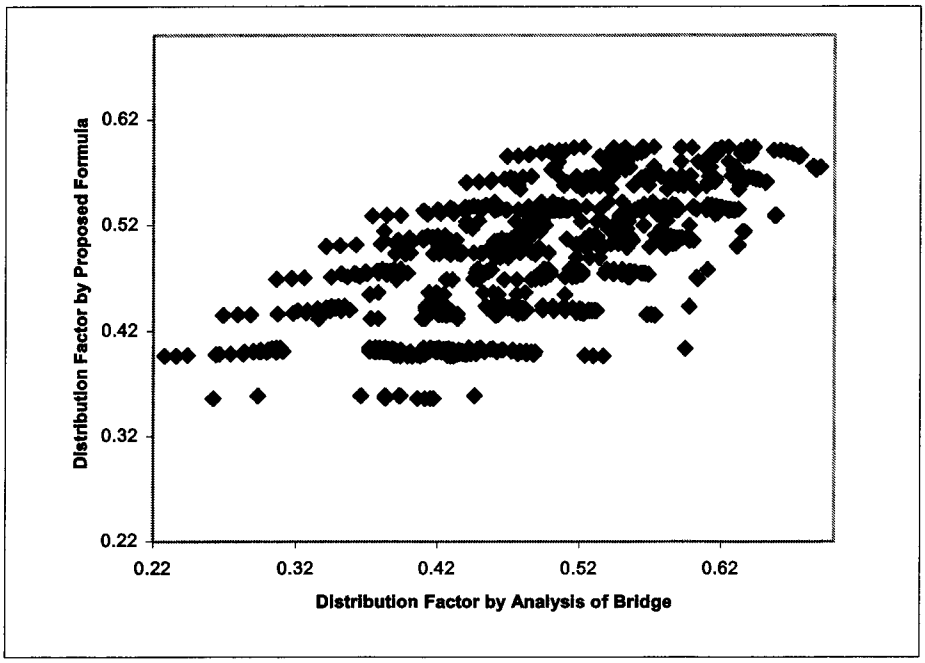


a. Distribution factor

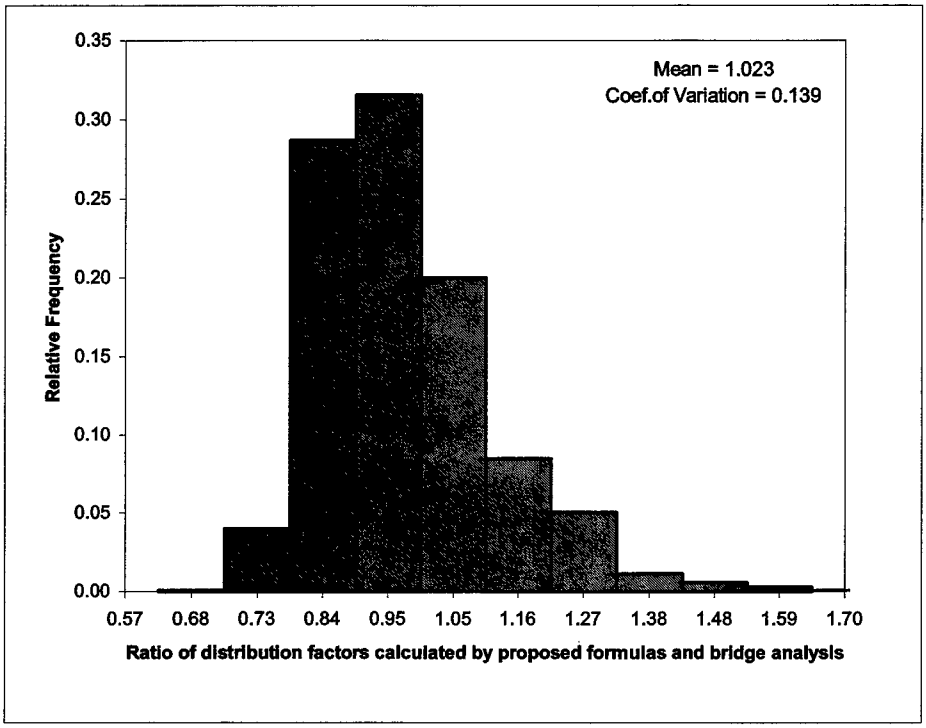


b. Ratio of distribution factors

Figure 70. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in exterior girders for single lane

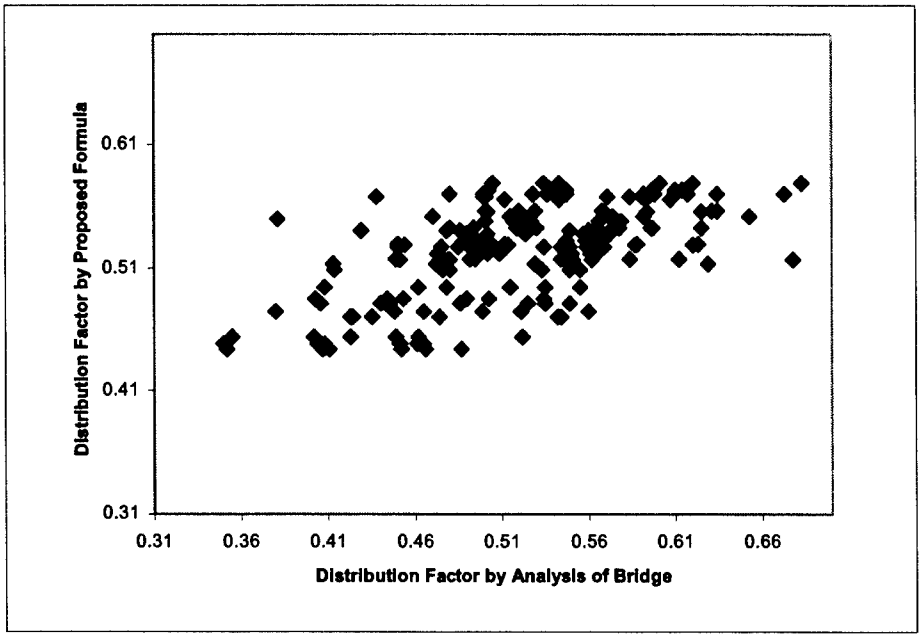


a. Distribution factor

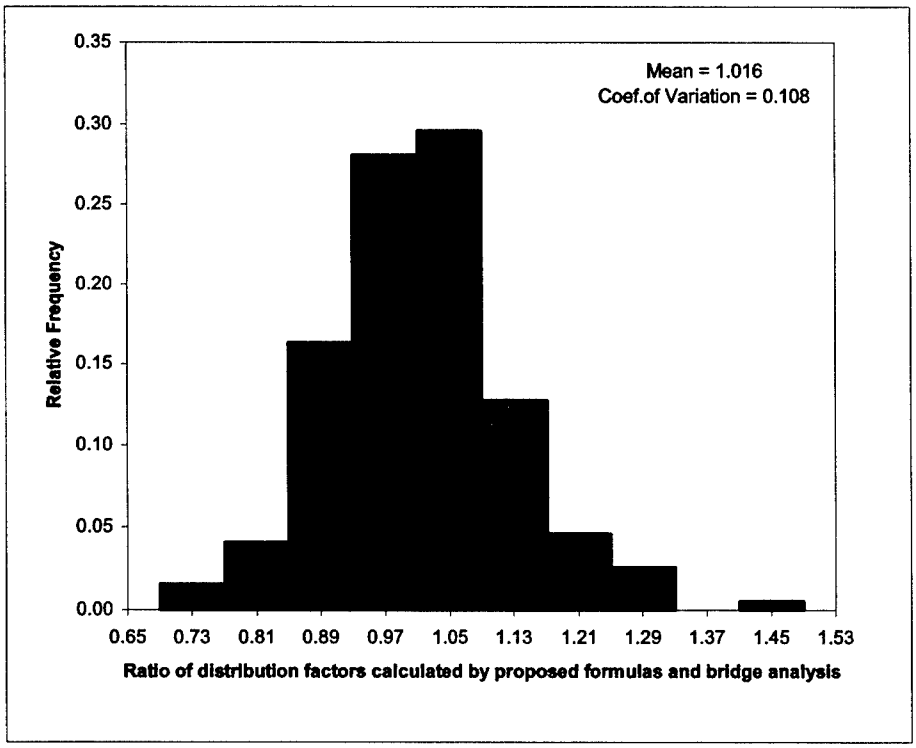


b. Ratio of distribution factors

Figure 71. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in exterior girders for single lane

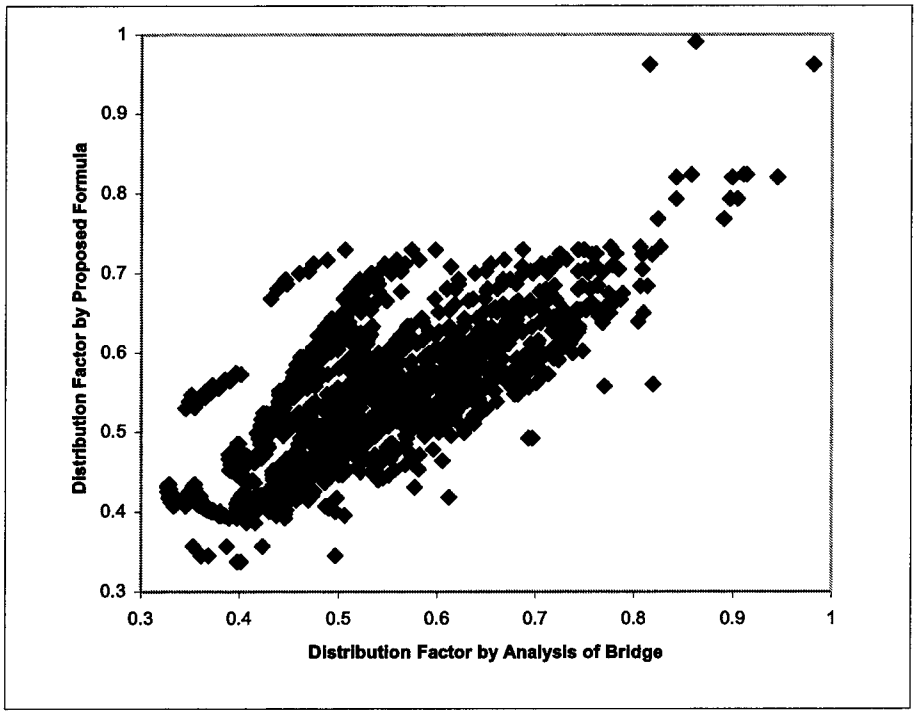


a. Distribution factor

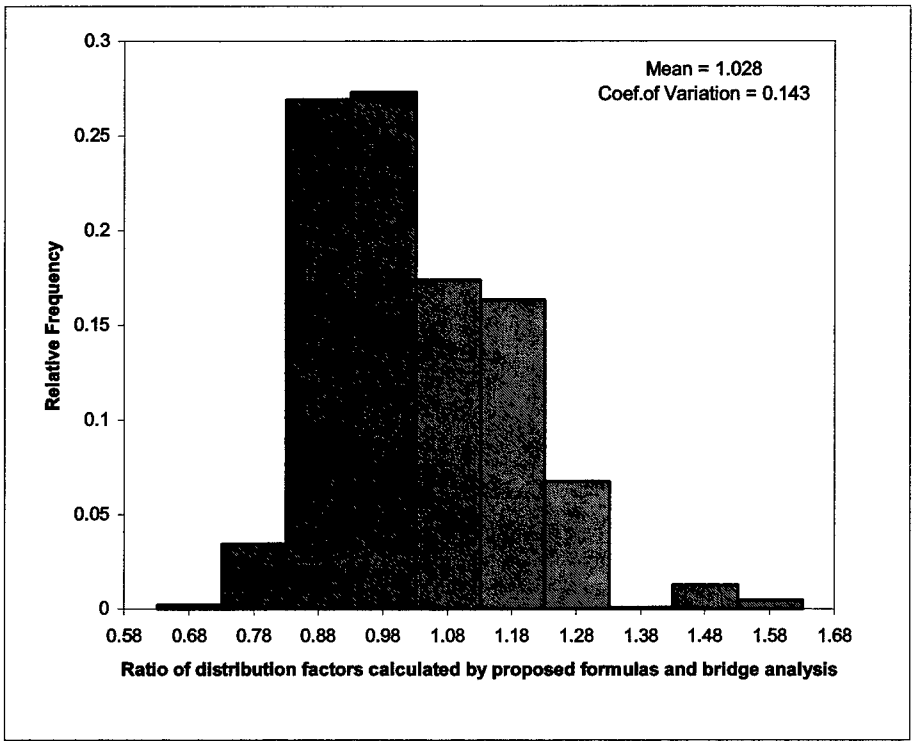


b. Ratio of distribution factors

Figure 72. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in exterior girders for single lane

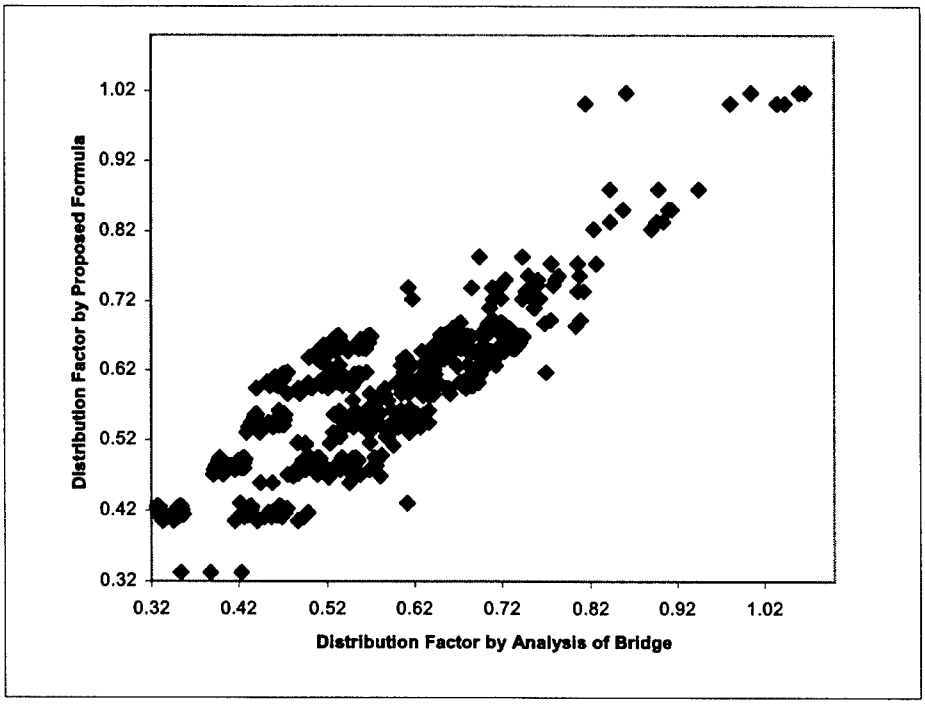


a. Distribution factor

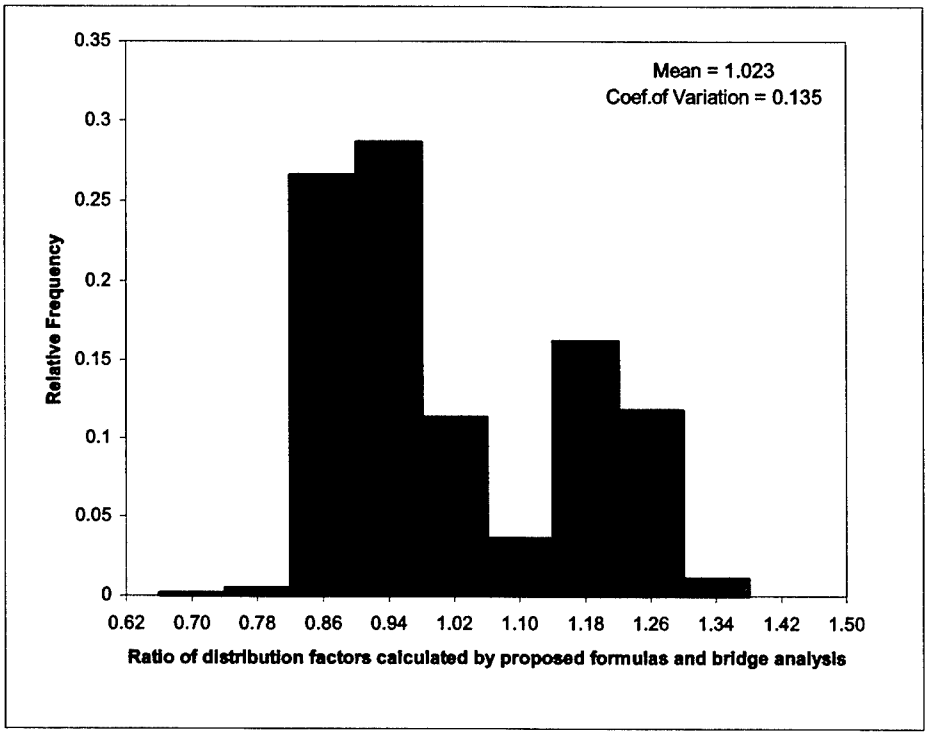


b. Ratio of distribution factors

Figure 73. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, bending moment in exterior girders for multiple lane

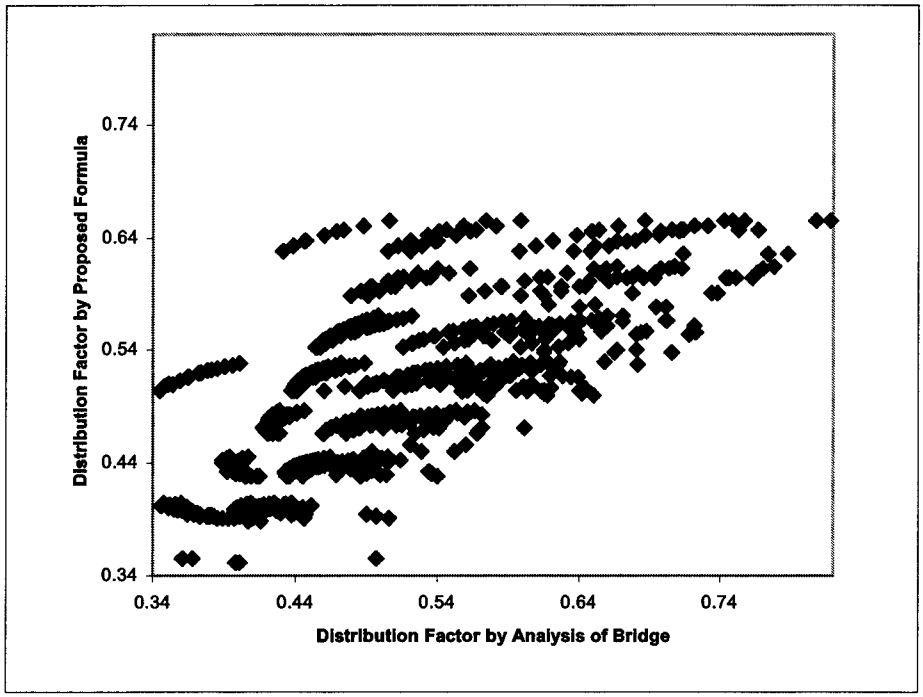


a. Distribution factor

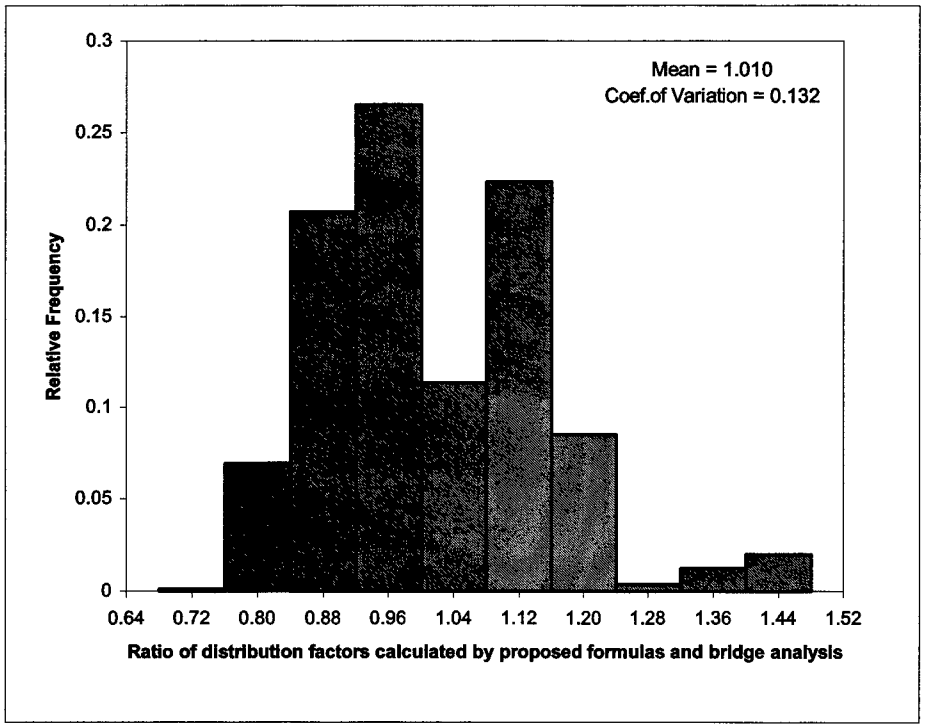


b. Ratio of distribution factors

Figure 74. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, bending moment in exterior girders for multiple lane

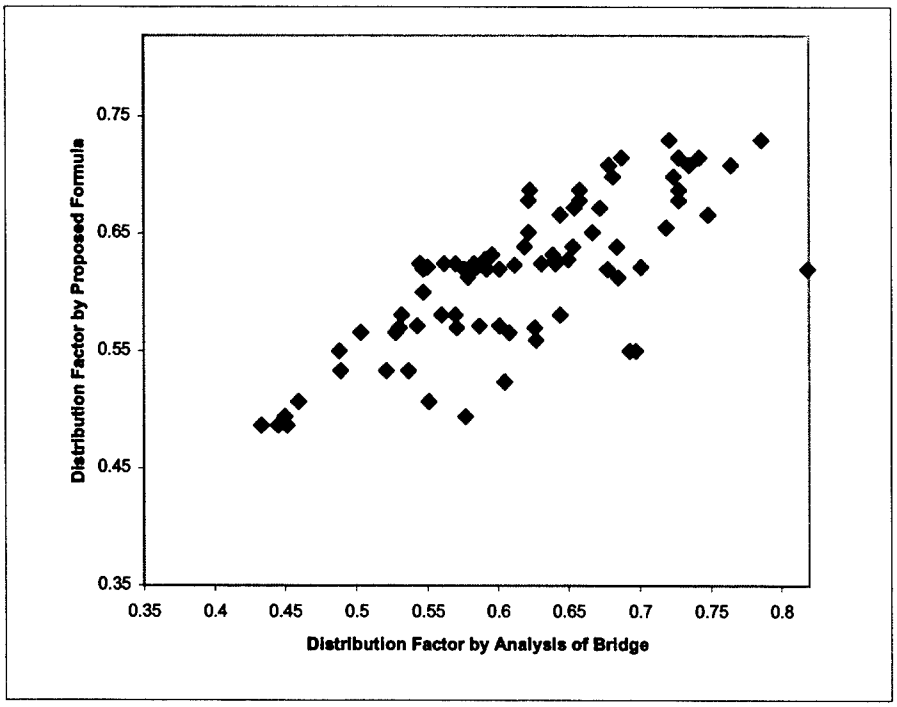


a. Distribution factor

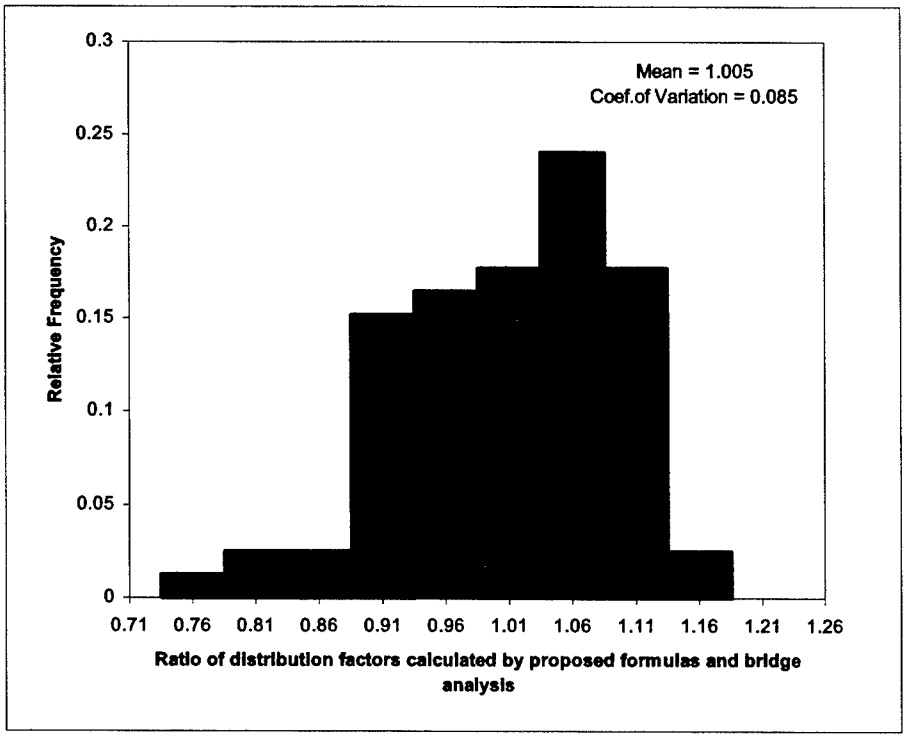


b. Ratio of distribution factors

Figure 75. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, bending moment in exterior girders for multiple lane

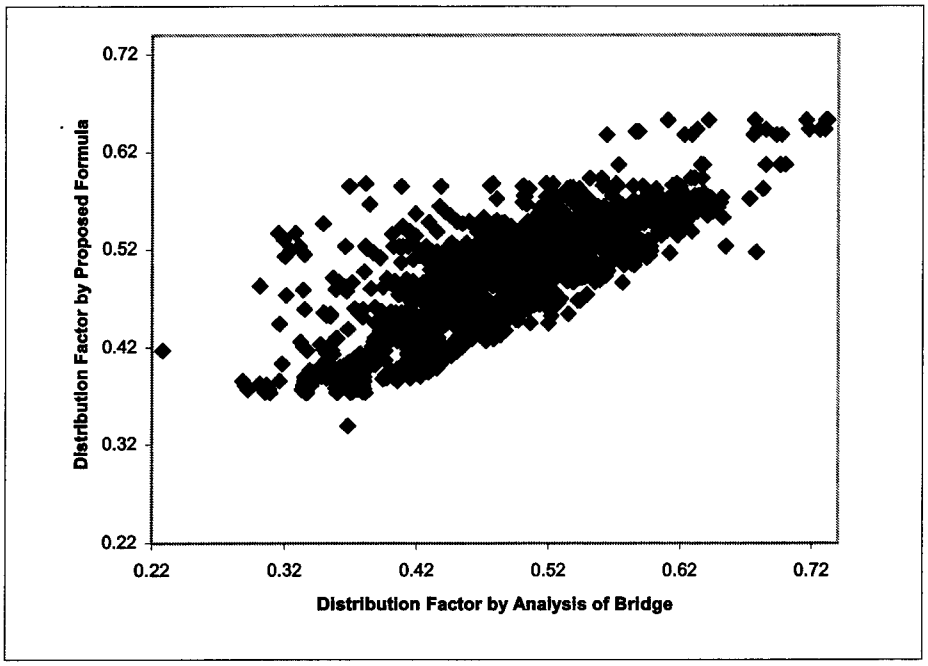


a. Distribution factor

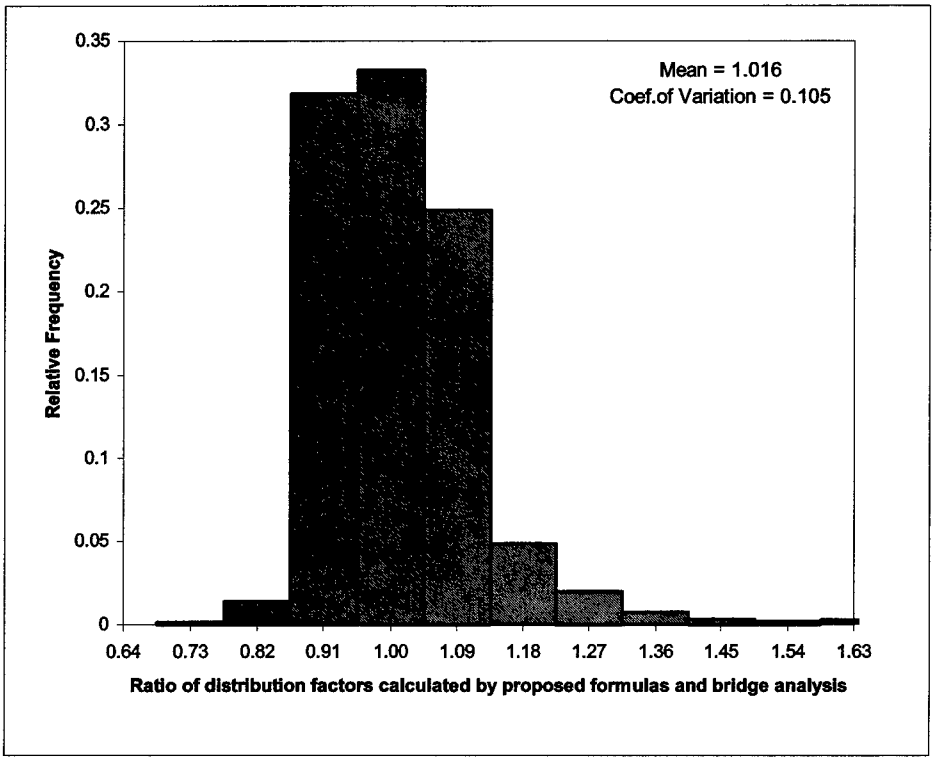


b. Ratio of distribution factors

Figure 76. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, bending moment in exterior girders for multiple lane

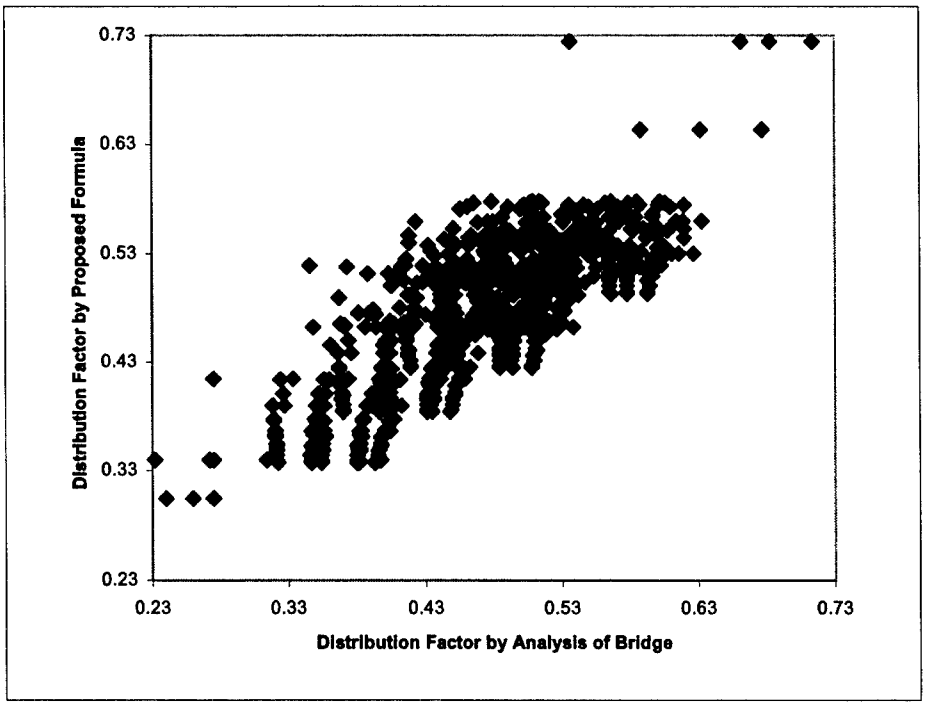


a. Distribution factor

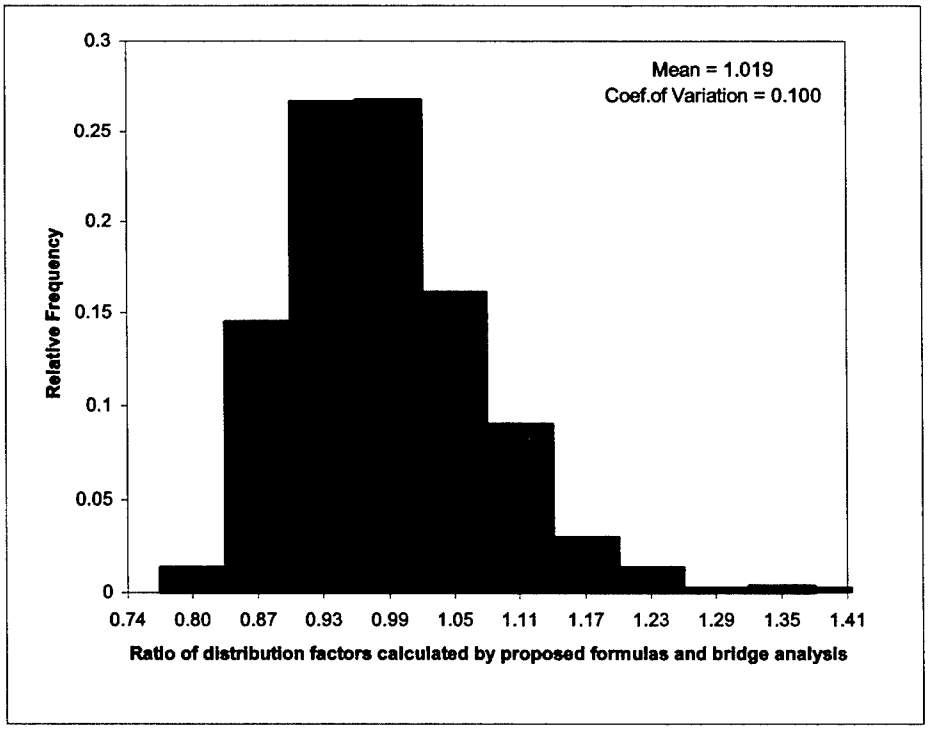


b. Ratio of distribution factors

Figure 77. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in exterior girders for single lane

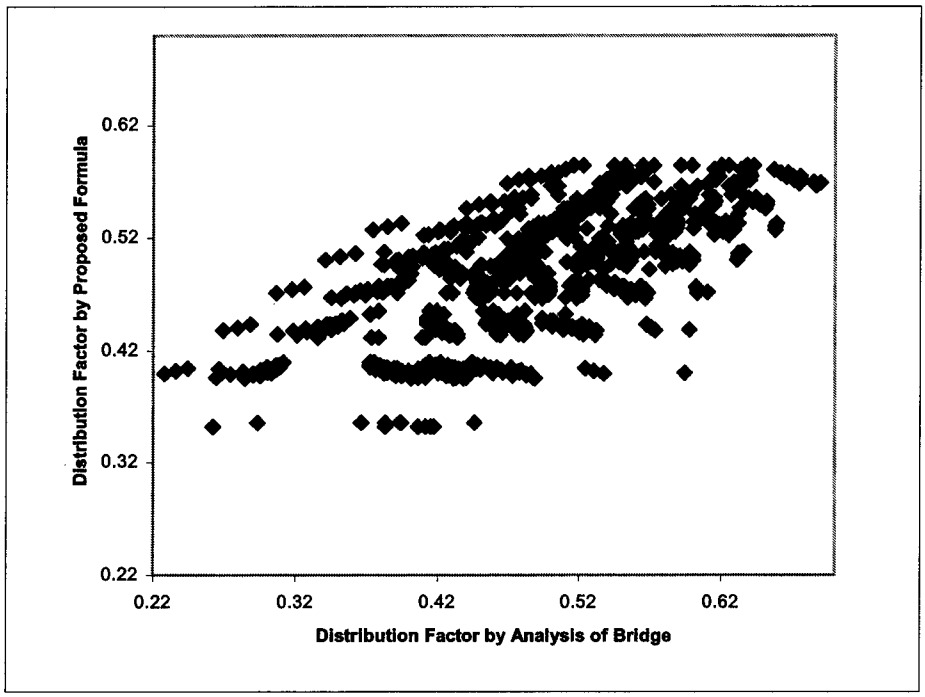


a. Distribution factor

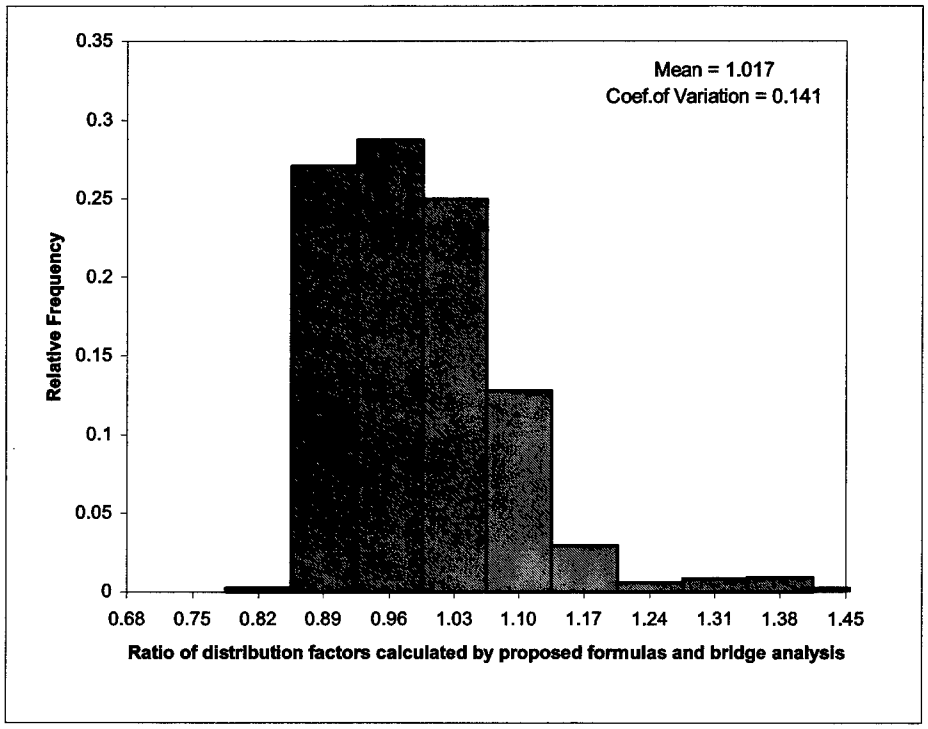


b. Ratio of distribution factors

Figure 78. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in exterior girders for single lane

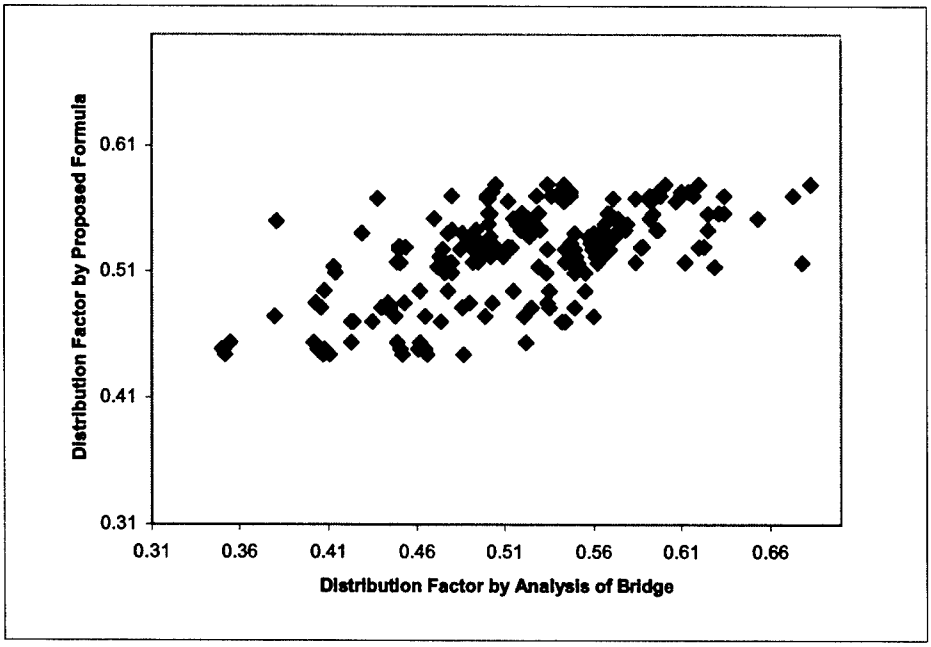


a. Distribution factor

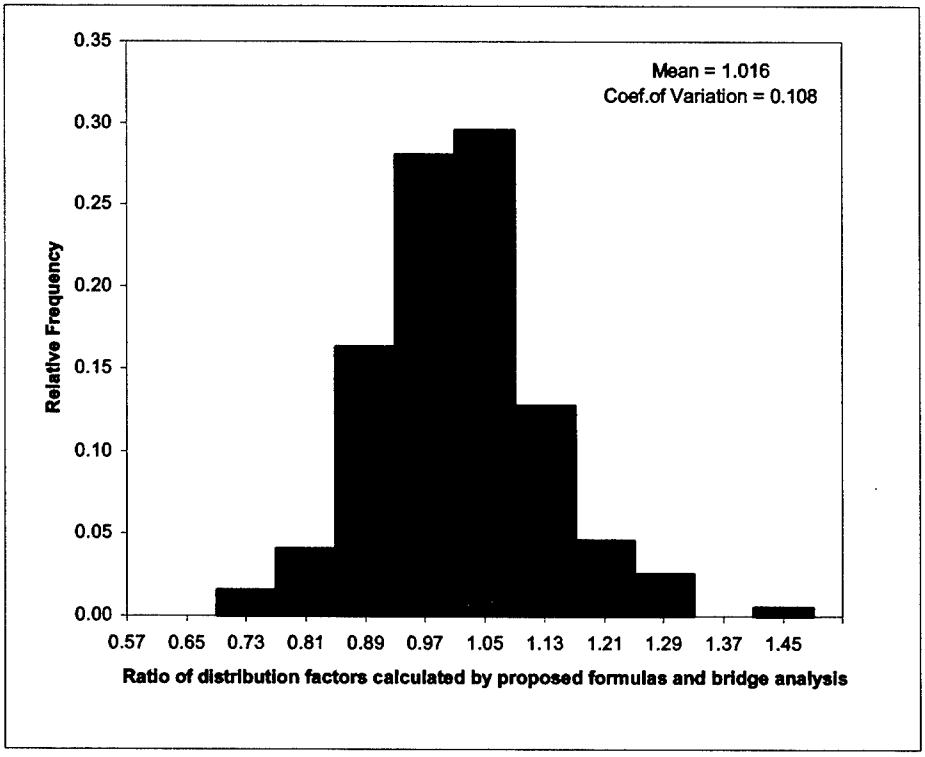


b. Ratio of distribution factors

Figure 79. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed, shear in exterior girders for single lane

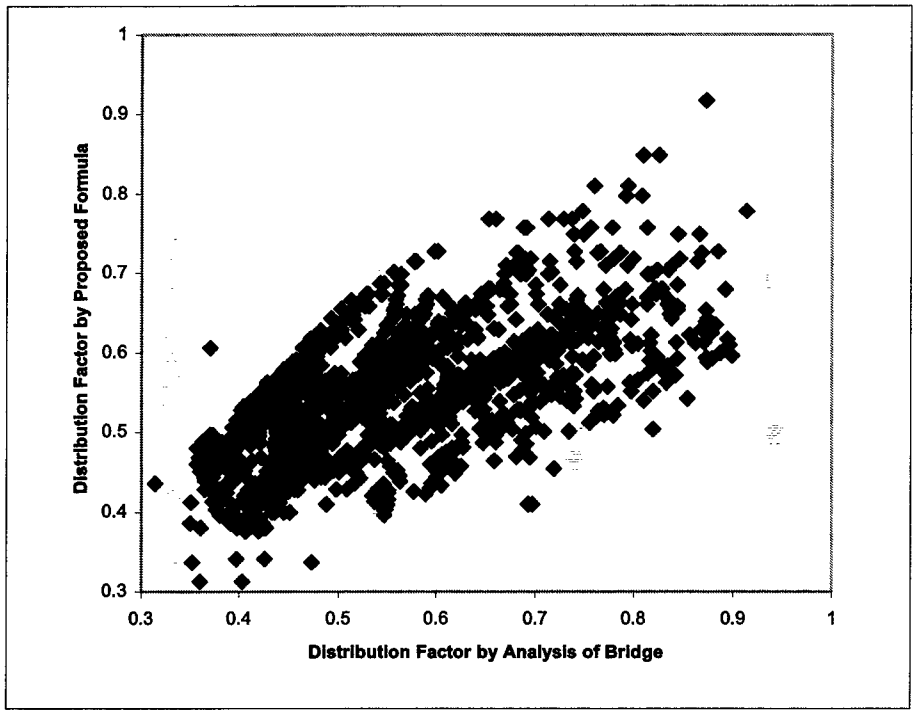


a. Distribution factor

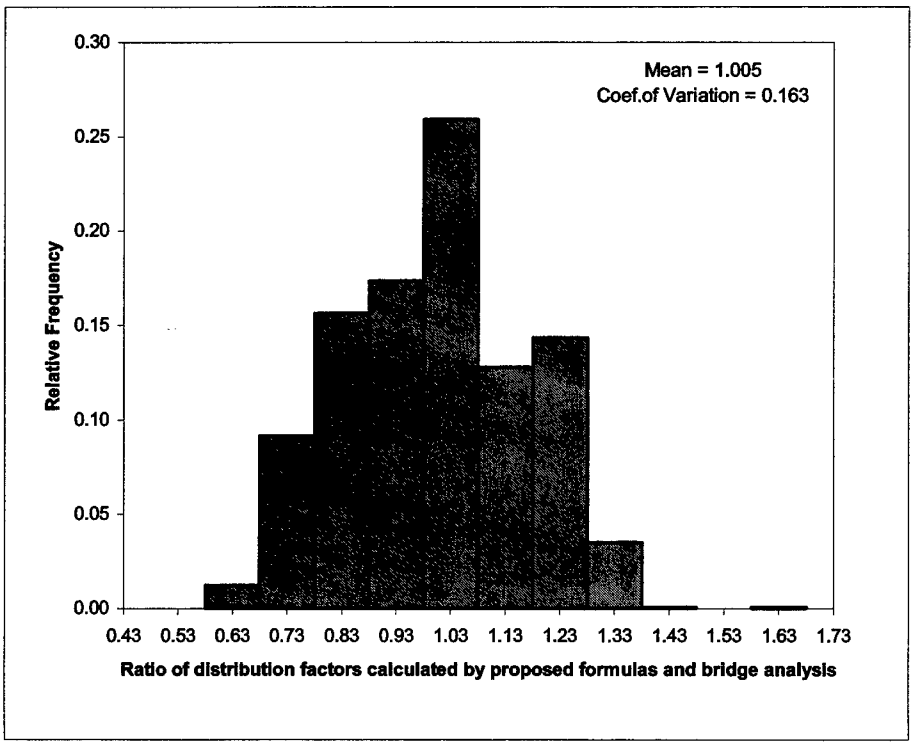


b. Ratio of distribution factors

Figure 80. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in exterior girders for single lane

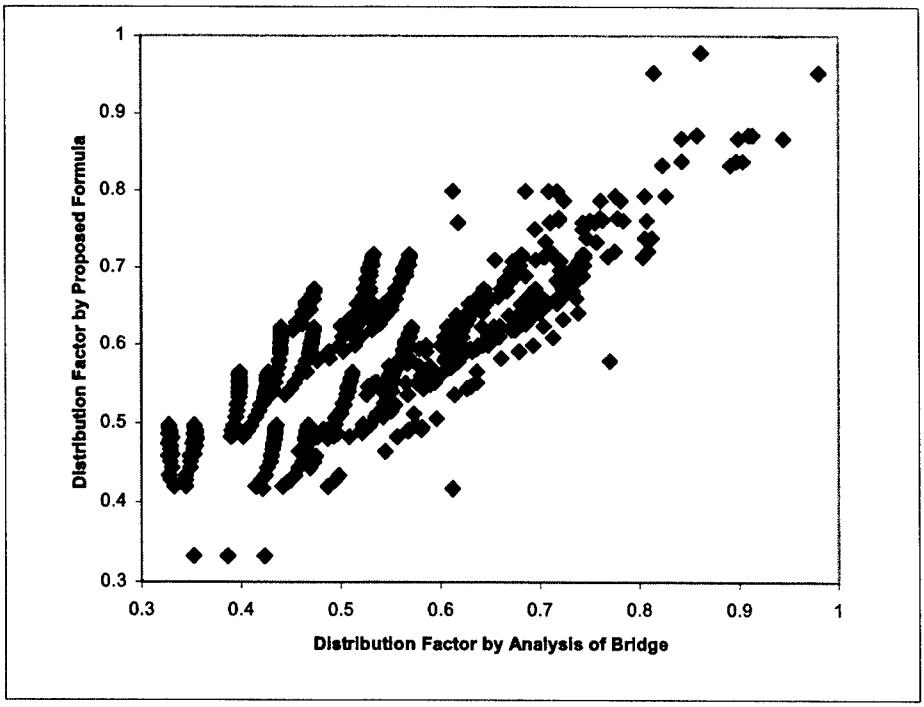


a. Distribution factor

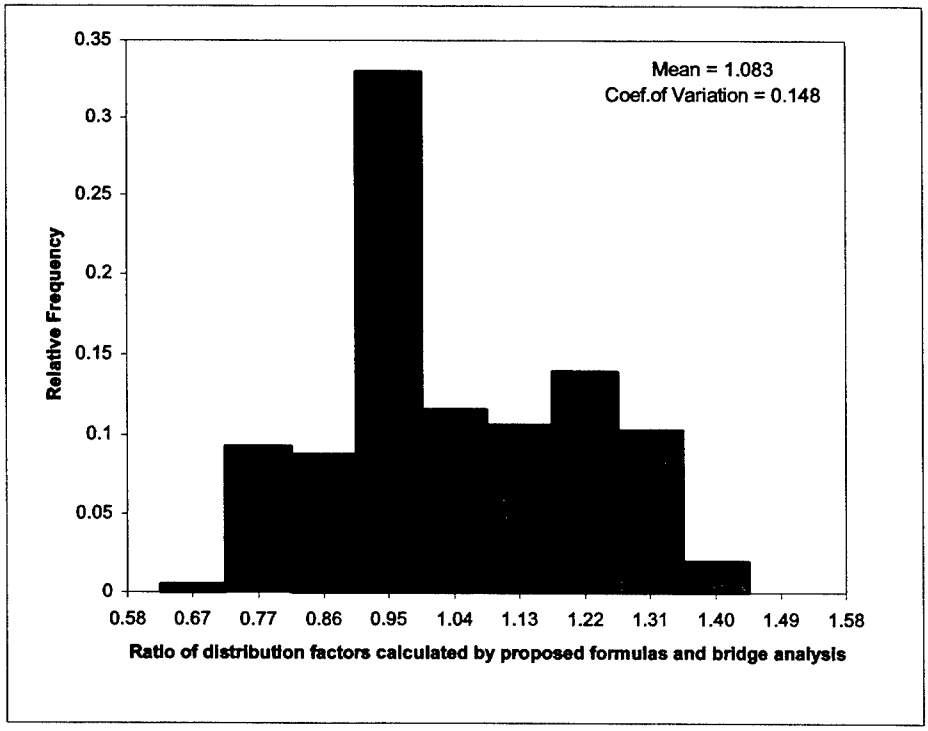


b. Ratio of distribution factors

Figure 81. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, all beam bridges, shear in exterior girders for multiple lane

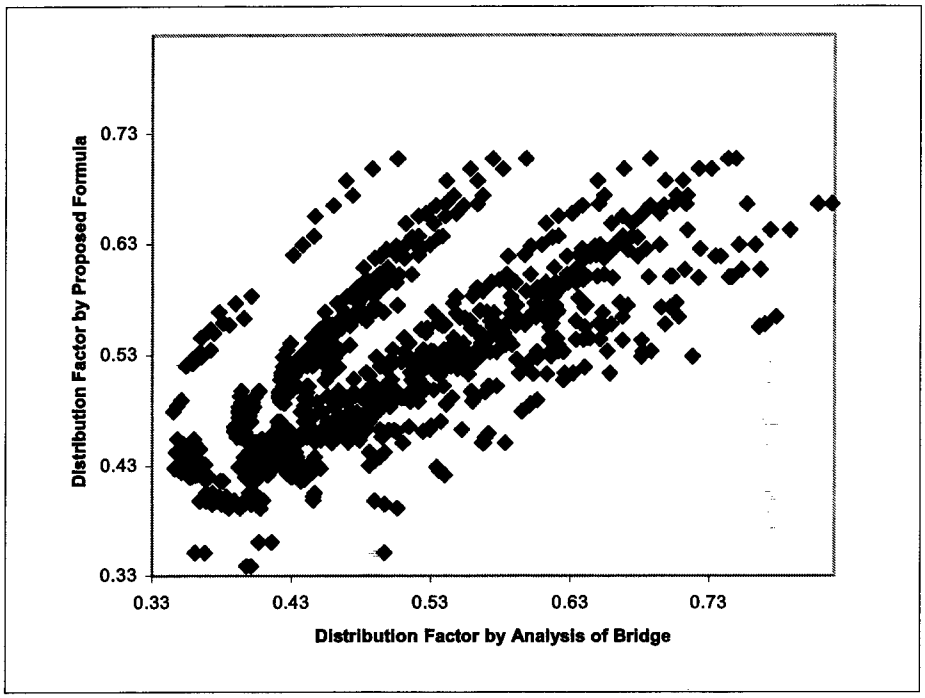


a. Distribution factor

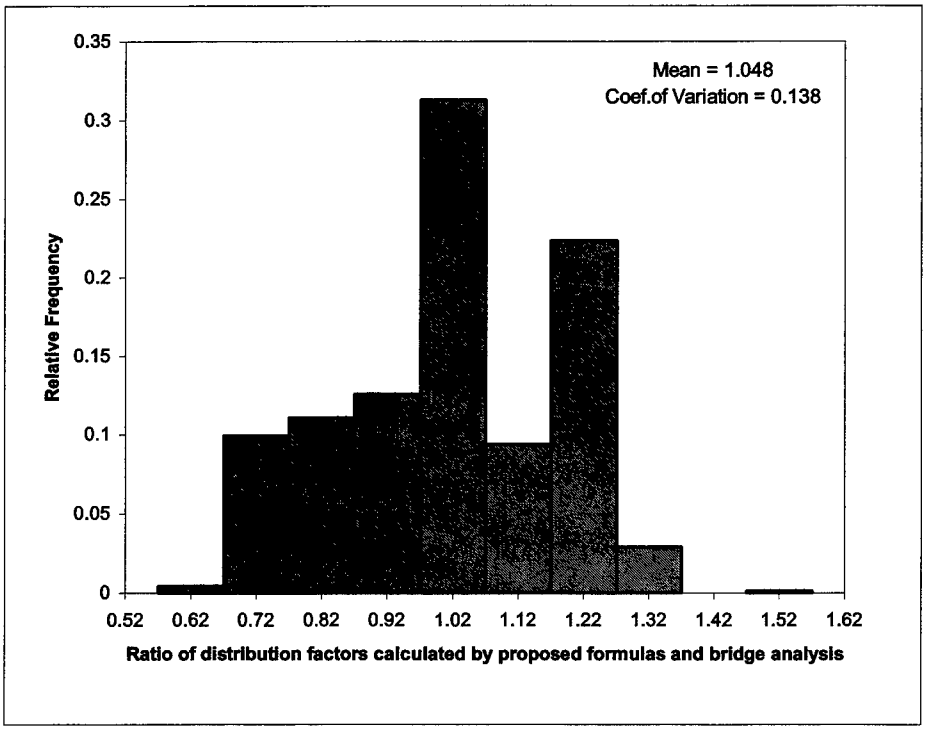


b. Ratio of distribution factors

Figure 82. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, steel girder, shear in exterior girders for multiple lane

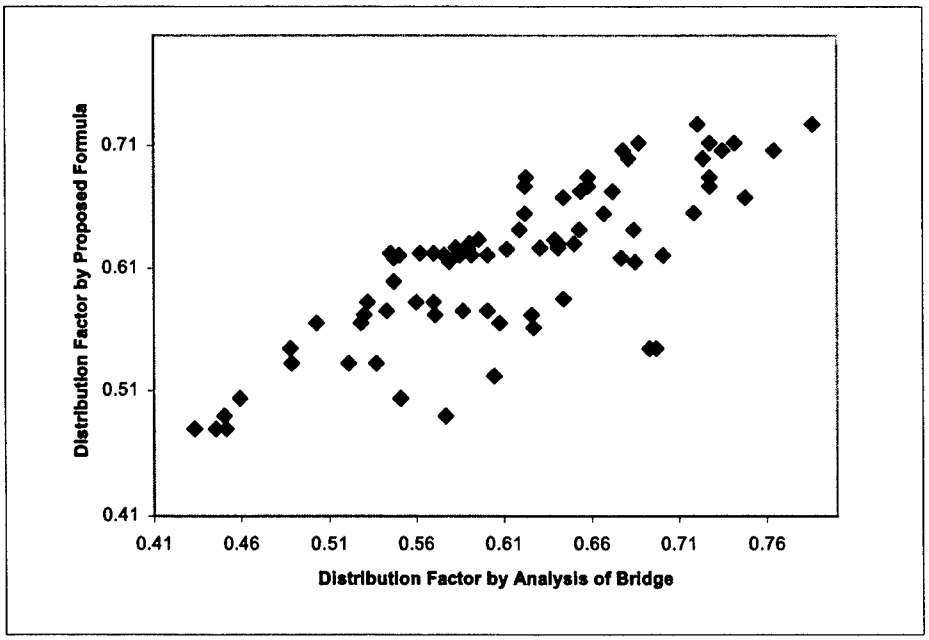


a. Distribution factor

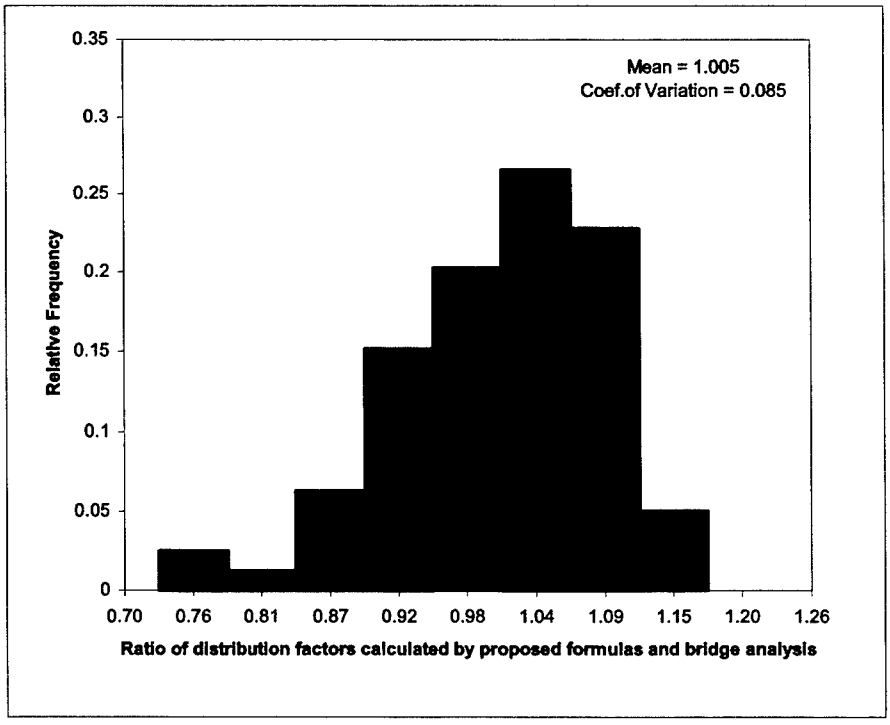


b. Ratio of distribution factors

Figure 83. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, prestressed girder, shear in exterior girders for multiple lane



a. Distribution factor



b. Ratio of distribution factors

Figure 84. Comparison of distribution factors calculated by proposed formulas and bridge analysis for all vehicles, concrete T-beam, shear in exterior girders for multiple lane

11 Proposed Distribution Factors Versus Pre-LRFD and Post-LRFD Distribution Factors

It is of interest to compare the values of the distribution factors calculated by the new proposed formulas developed for the military vehicles with the values calculated according to the pre-and post-LRFD AASHTO specifications for the civilian vehicles. The distribution factor formulas given in the 1994 and earlier versions of the AASHTO Standard specifications are considered as the pre-LRFD distribution factors. The factors defined in the 1996 AASHTO Standard Specification are considered as the post-LRFD distribution factors. For the bending moment in an interior girder for the single loading case, these formulas are given in Table 14. No comparison is made for the exterior girders, or multiple-lane-loading case or the shear force distribution factors.

Table 14
Bending Moment Load Distribution Factor Formulas for Interior Girders Single Lane Loading Scenario

Steel	$\frac{S}{7}$	$0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{Kg}{12.0Lt^3}\right)^{0.1}$
Prestressed	$\frac{S}{7}$	$0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{Kg}{12.0Lt^3}\right)^{0.1}$
T-Beam	$\frac{S}{6.5}$	$0.06+\left(\frac{S}{14}\right)^{0.4}\left(\frac{S}{L}\right)^{0.3}\left(\frac{Kg}{12.0Lt^3}\right)^{0.1}$

The comparison of the load factors is made both quantitatively in the tabular form and qualitatively in the graphical form. Tables 15 through 19 show the mean and coefficient of variation values of the distribution factor calculated by harmonic analysis (most exact), proposed new formulas for military vehicles, LRFD formulas in AASHTO 1996, and the pre-LRFD formulas in 1994 and earlier versions of AASHTO specifications. Each table is for a particular type of vehicle. Only the single lane loading case is considered. Graphically the mean values for the bending moment in these tables are compared in Figures 85 through 89. Each figure corresponds to a table. That is, Figure 85 depicts the mean values in Table 15, Figure 86 depicts the values in Table 16, and so on, as is shown in the tabulation below. These figures indicate that mean values calculated by the harmonic analysis and the proposed formulas are quite close to each other. When compared with the more accurate harmonic analysis, usually the pre-LRFD formulas tend to over estimate and the post-LRFD formulas usually tend to underestimate the values of the distribution factors.

Table No.	Figure No.	Vehicle Type
15	85	PLS and HEMMT
16	86	HETS
17	87	Abrams
18	88	M113 and Bradley
19	89	All vehicles

Table 15
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders PLS and HEMMT Vehicles

		Single Lane Loading			
Bridge Type	Coefficients	Harmonic Analysis	New Formulas	LRFD Formulas	Non-LRFD Formulas
All Beam	Mean	0.465	0.477	0.393	0.498
	C.O.V.	0.243	0.160	0.201	0.277
Steel Girder	Mean	0.400	0.396	0.364	0.464
	C.O.V.	0.135	0.077	0.186	0.265
Prestressed Girder	Mean	0.495	0.500	0.393	0.478
	C.O.V.	0.220	0.182	0.178	0.274
Concrete T-Beam	Mean	0.557	0.555	0.442	0.548
	C.O.V.	0.259	0.199	0.172	0.221

Table 16
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders HETS Vehicle

Bridge Type	Coefficients	Single Lane Loading			
		Harmonic Analysis	New Formulas	LRFD Formulas	Non-LRFD Formulas
All Beam	Mean	0.439	0.436	0.377	0.463
	C.O.V.	0.245	0.217	0.199	0.266
Steel Girder	Mean	0.382	0.382	0.366	0.467
	C.O.V.	0.154	0.144	0.190	0.270
Prestressed Girder	Mean	0.474	0.480	0.393	0.474
	C.O.V.	0.229	0.194	0.177	0.270
Concrete T-Beam	Mean	0.472	0.475	0.467	0.571
	C.O.V.	0.194	0.103	0.147	0.179

Table 17
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders Abrams Vehicle

Bridge Type	Coefficients	Single Lane Loading			
		Harmonic Analysis	New Formulas	LRFD Formulas	Non-LRFD Formulas
All Beam	Mean	0.398	0.399	0.377	0.463
	C.O.V.	0.221	0.204	0.199	0.266
Steel Girder	Mean	0.369	0.370	0.361	0.459
	C.O.V.	0.120	0.109	0.174	0.263
Prestressed Girder	Mean	0.425	0.429	0.397	0.477
	C.O.V.	0.233	0.210	0.196	0.276
Concrete T-Beam	Mean	0.440	0.444	0.467	0.571
	C.O.V.	0.161	0.142	0.147	0.179

Table 18
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders M113 and Bradley Vehicles

Bridge Type	Coefficients	Single Lane Loading			
		Harmonic Analysis	New Formulas	LRFD Formulas	Non-LRFD Formulas
All Beam	Mean	0.434	0.434	0.378	0.462
	C.O.V.	0.236	0.207	0.205	0.266
Steel Girder	Mean	0.394	0.393	0.364	0.463
	C.O.V.	0.143	0.143	0.185	0.272
Prestressed Girder	Mean	0.467	0.466	0.396	0.476
	C.O.V.	0.238	0.213	0.183	0.277
Concrete T-Beam	Mean	0.476	0.509	0.474	0.566
	C.O.V.	0.180	0.151	0.165	0.178

Table 19
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor obtained with Harmonic Analysis, LRFD, Non-LRFD, and New Formulas for Interior Girders All Vehicles

		Single Lane Loading			
Bridge Type	Coefficients	Harmonic Analysis	New Formulas	LRFD Formulas	Non-LRFD Formulas
All Beam	Mean	0.437	0.436	0.383	0.476
	C.O.V.	0.226	0.184	0.182	0.256
Steel Girder	Mean	0.390	0.395	0.364	0.463
	C.O.V.	0.142	0.120	0.184	0.267
Prestressed Girder	Mean	0.470	0.466	0.483	0.478
	C.O.V.	0.235	0.200	0.188	0.276
Concrete T-Beam	Mean	0.483	0.482	0.576	0.569
	C.O.V.	0.314	0.230	0.400	0.365

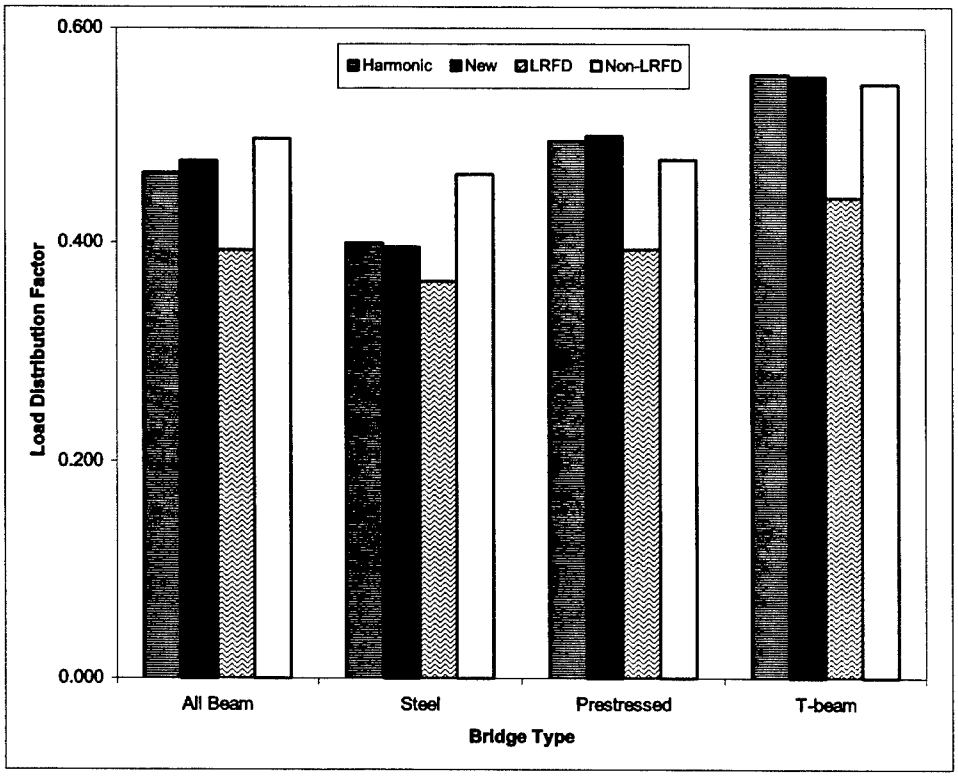


Figure 85. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFd and non-LRFD formulas for PLS and HEMTT vehicles, all bridges, bending moment in interior girders for single lane

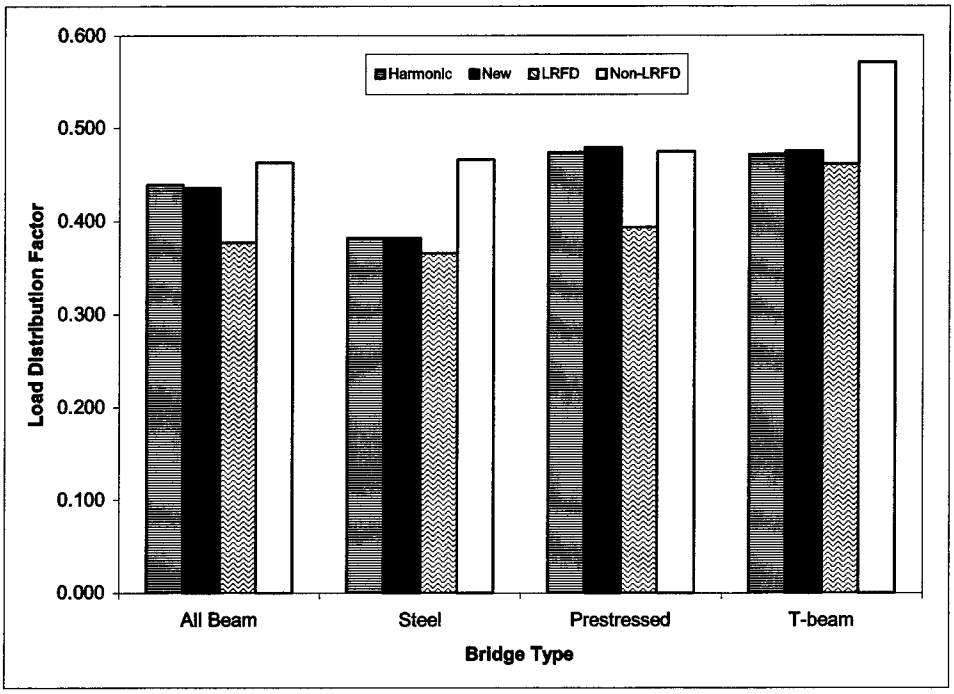


Figure 86. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for HETS vehicle, all bridges, bending moment in interior girders for single lane

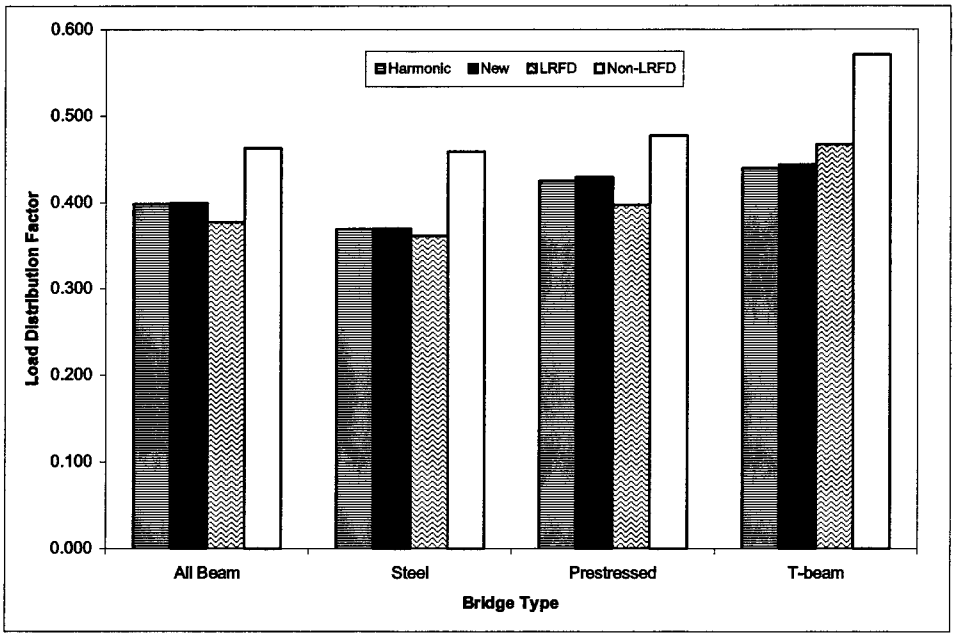


Figure 87. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for Abrams vehicle, all bridges, bending moment in interior girders for single lane

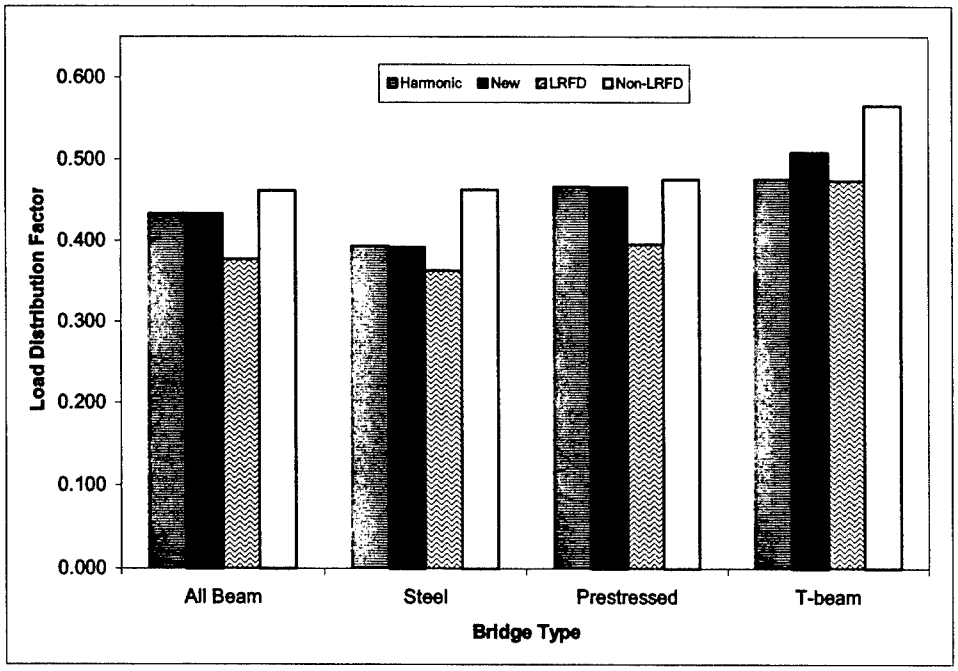


Figure 88. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for M113 and Bradley vehicles, all bridges, bending moment in interior girders for single lane

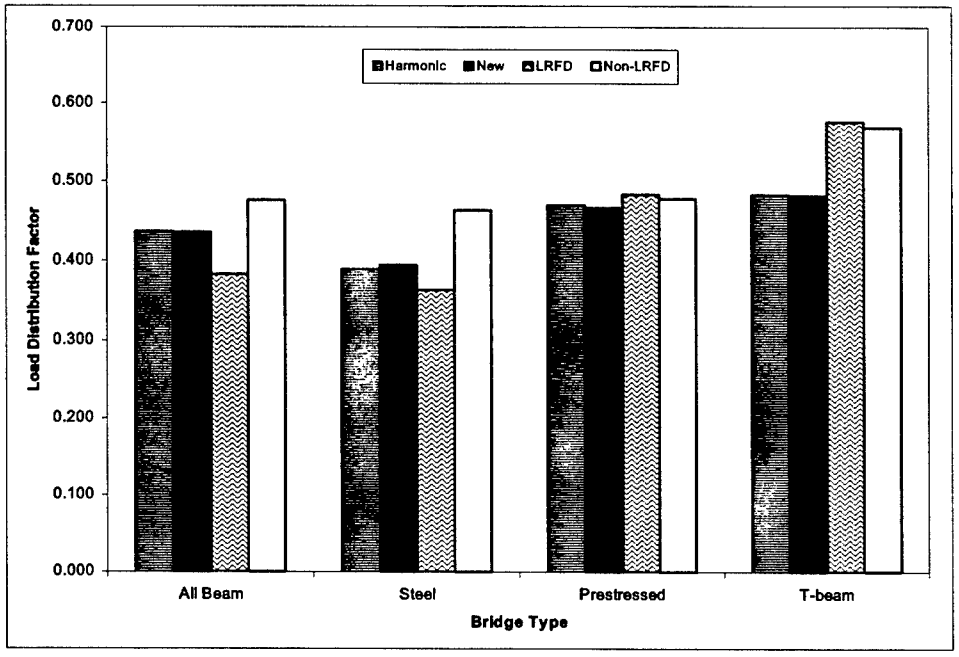


Figure 89. Comparison of mean values of the distribution factors calculated by bridge analysis, proposed formulas, LRFD and non-LRFD formulas for All vehicles, all bridges, bending moment in interior girders for single lane

Another approach to compare various distribution factor formulas is to obtain the ratio of the distribution factors calculated by the formulas to factor calculated by the direct analysis. This was done earlier in the previous section when the distribution factors calculated by the proposed formulas were evaluated vis-à-vis the values calculated by direct analysis. Tables 20 through 24 show the mean and coefficient of variation values of the distribution factor ratio calculated by the proposed, post-LRFD, and pre-LRFD formulas. The denominator of these ratios is the distribution factor calculated by the harmonic analysis. A mean value close to 1.0 with a small coefficient of variation implies that the values calculated by the formula are close to the values calculated by the analysis. The frequency distribution of these ratios is shown by the histograms shown in Figures 90 through 109. The following tabulation lists the figure numbers associated with each table.

Table No.	Figure No.	Vehicle Type
20	90 through 93	PLS and HEMMT
21	94 through 97	HETS
22	98 through 101	Abrams
23	102 through 105	M113 and Bradley
24	106 through 109	All vehicles

Each figure has three parts. The top histograms in these figures are the same as those discussed in the previous section. They show the comparison of the distribution factor values calculated by the proposed formulas with those calculated by the analysis. The middle histogram shows the comparison of the post-LRFD values with the analytical values, and the bottom histogram shows this comparison of pre-LRFD values with the analytical values. The mean and coefficient values given in the tables are also shown on each figure. Also shown on each histogram is a coefficient, which is similar to the skewness coefficient but here it is defined with respect to the ratio of 1.0 (and not the mean value) as follows:

$$k = \frac{\sum_{i=1}^{n} (x_i - 1)^3}{n\sigma^3}$$

where k is the skewness coefficient, x_i is the i^{th} distribution factor ratio value, n is the number of bridges analyzed, and σ is the standard deviation of the distribution factor ratio. A positive value of this coefficient means that the frequency distribution of the ratio is skewed to the right, with more values being higher than 1.0. Similarly, a negative value means that the frequency distribution is skewed to the left, with more values being less than 1.0. As indicated before, on an average the post-LRFD formulas tend to underestimate and the pre-LRFD formulas tend to overestimate the distribution factor values for the military vehicles. Also, the simple pre-LRFD formulas show a larger dispersion in the ratio; it implies that there is a larger uncertainty associated with the values

calculated by these formulas. Compared to the pre- and post-LRFD formulas, the proposed formulas provide the distribution factor values closest to the analytically calculated values with least dispersion and relatively smaller underestimation of the factor values.

Table 20
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders PLS and HEMMT Vehicles

Bridge Type	Coefficients	Single Lane Loading		
		New/Harmonic	LRFD/Harmonic	Non-LRFD/Harmonic
All Beam	Mean	1.050	0.861	1.083
	C.O.V.	0.159	0.175	0.249
Steel Girder	Mean	0.999	0.911	1.157
	C.O.V.	0.078	0.147	0.226
Prestressed Girder	Mean	1.023	0.806	0.964
	C.O.V.	0.115	0.118	0.184
Concrete T-beam	Mean	1.021	0.817	1.006
	C.O.V.	0.170	0.170	0.186

Table 21
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders HETS Vehicle

Bridge Type	Coefficients	Single Lane Loading		
		New/Harmonic	LRFD/Harmonic	Non-LRFD/Harmonic
All Beam	Mean	1.004	0.872	1.062
	C.O.V.	0.107	0.107	0.172
Steel Girder	Mean	1.002	0.954	1.207
	C.O.V.	0.047	0.088	0.174
Prestressed Girder	Mean	1.023	0.843	1.001
	C.O.V.	0.105	0.110	0.167
Concrete T-Beam	Mean	1.008	0.998	1.225
	C.O.V.	0.063	0.068	0.159

Table 22
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders Abrams Vehicle

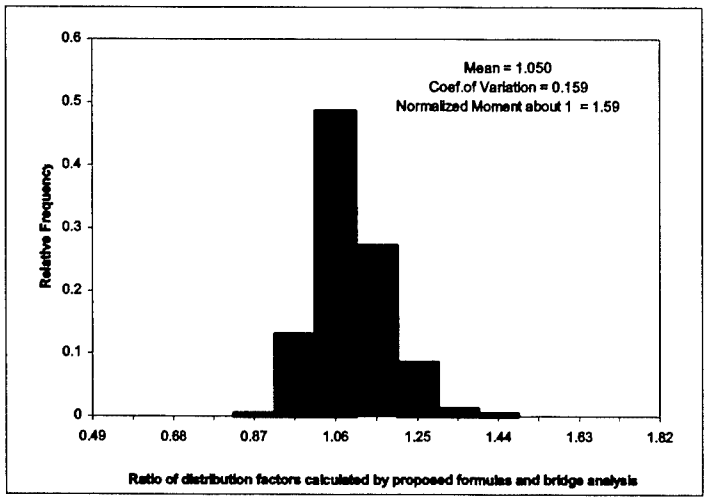
Bridge Type	Coefficients	Single Lane Loading		
		New/Harmonic	LRFD/Harmonic	Non-LRFD/Harmonic
All Beam	Mean	1.007	0.954	1.155
	C.O.V.	0.069	0.094	0.124
Steel Girder	Mean	1.003	0.975	1.226
	C.O.V.	0.042	0.105	0.172
Prestressed Girder	Mean	1.019	0.951	1.117
	C.O.V.	0.091	0.134	0.123
Concrete T-Beam	Mean	1.015	1.066	1.304
	C.O.V.	0.074	0.073	0.131

Table 23
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders M113 and Bradley Vehicles

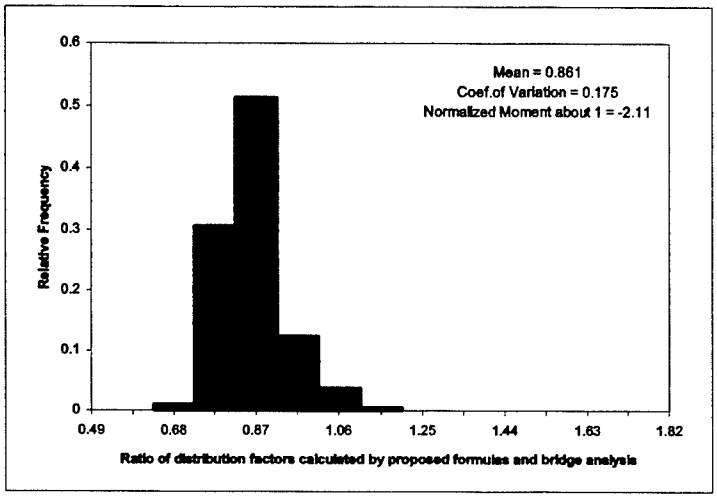
Bridge Type	Coefficients	Single Lane Loading		
		New/Harmonic	LRFD/Harmonic	Non-LRFD/Harmonic
All Beam	Mean	1.010	0.881	1.064
	C.O.V.	0.098	0.114	0.148
Steel Girder	Mean	1.001	0.921	1.162
	C.O.V.	0.059	0.106	0.185
Prestressed Girder	Mean	1.008	0.864	1.018
	C.O.V.	0.102	0.115	0.143
Concrete T-beam	Mean	1.073	1.004	1.201
	C.O.V.	0.119	0.112	0.148

Table 24
Mean and Coefficient of Variation Values for Bending Moment Load Distribution Factor Ratios obtained with LRFD, Non-LRFD, and New Formulas for Interior Girders All Vehicles

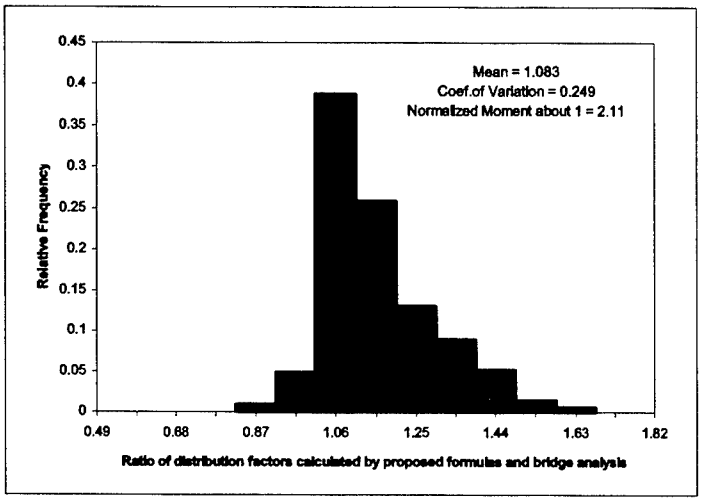
Bridge Type	Coefficients	Single Lane Loading		
		New/Harmonic	LRFD/Harmonic	Non-LRFD/Harmonic
All Beam	Mean	1.015	0.889	1.105
	C.O.V.	0.119	0.132	0.193
Steel Girder	Mean	1.018	0.931	1.177
	C.O.V.	0.066	0.112	0.192
Prestressed Girder	Mean	1.006	1.047	1.018
	C.O.V.	0.120	0.126	0.166
Concrete T-Beam	Mean	0.997	1.206	1.199
	C.O.V.	0.111	0.094	0.170



a. New formula

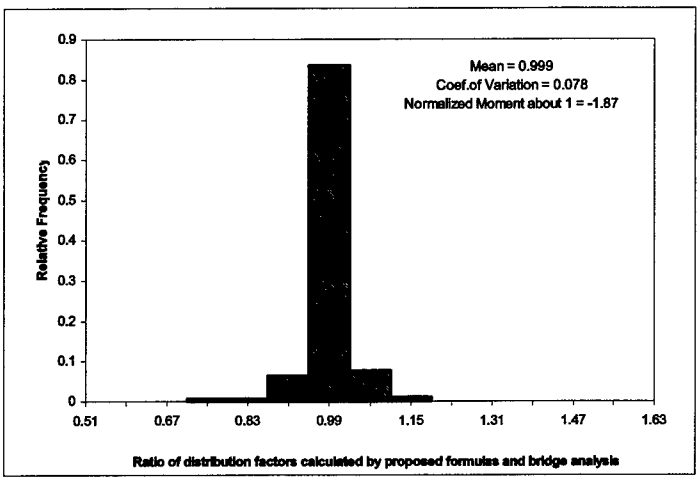


b. LRFD formula

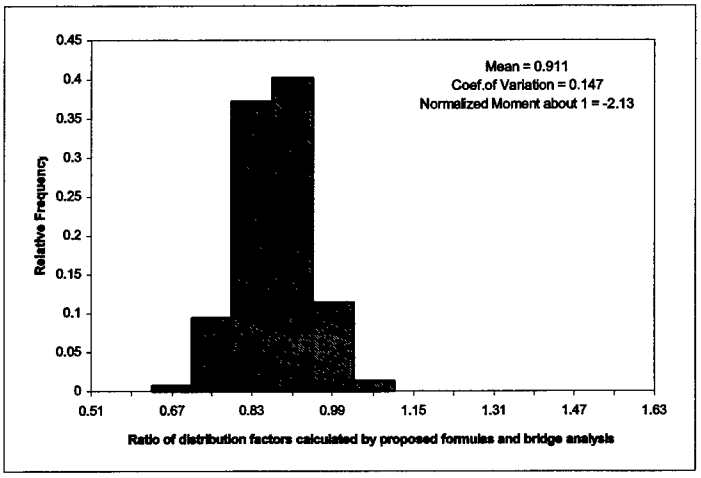


c. Non-LRDF formula

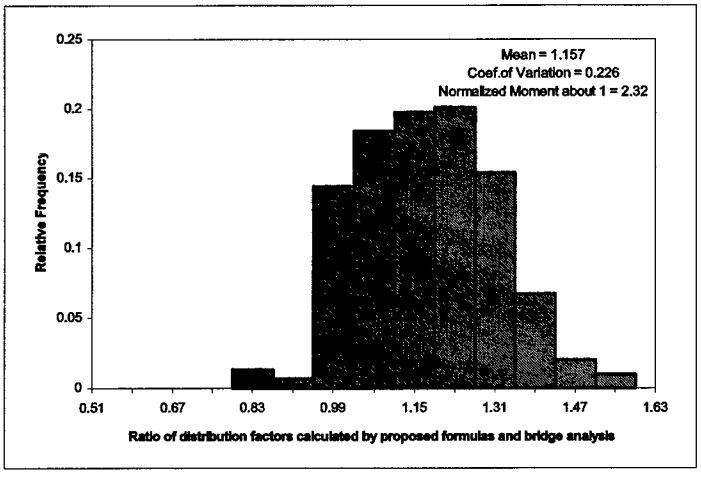
Figure 90. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, all beam bridges, bending moment in interior girders for single lane



a. New formula

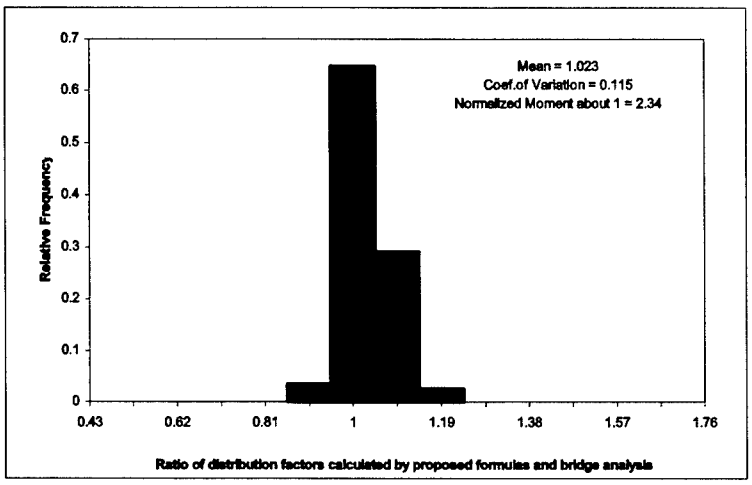


b. LRFD formula

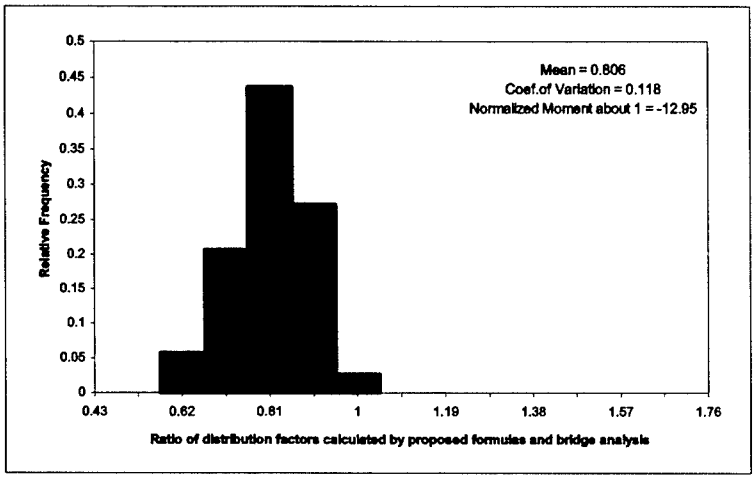


c. Non-LRDF formula

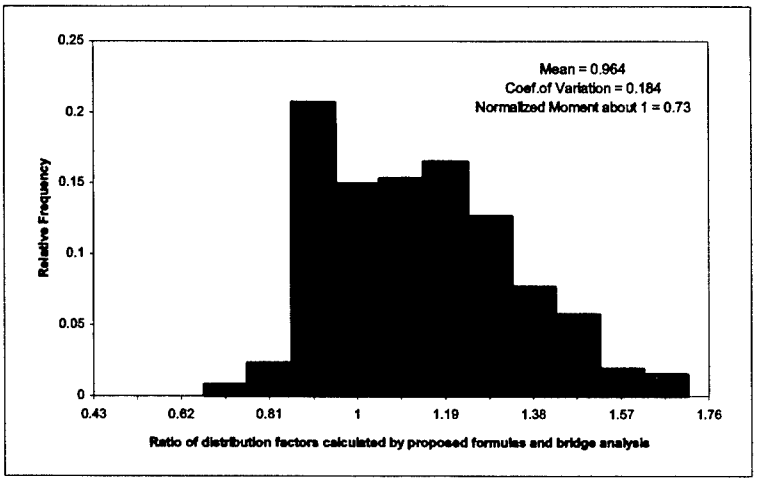
Figure 91. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, steel girder, bending moment in interior girders for single lane



a. New formula

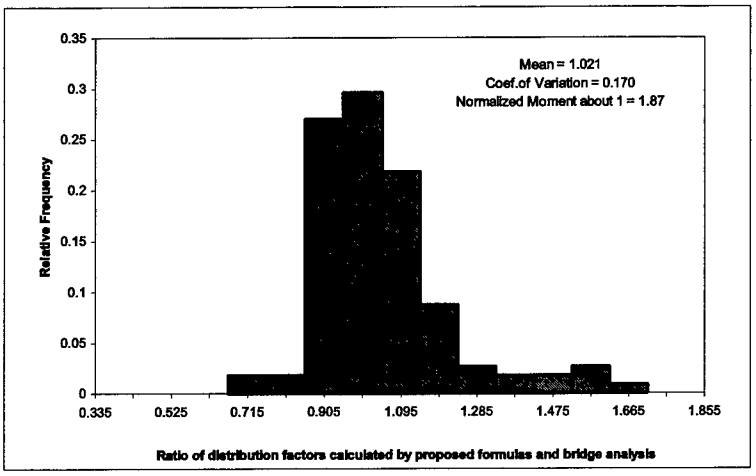


b. LRFD formula

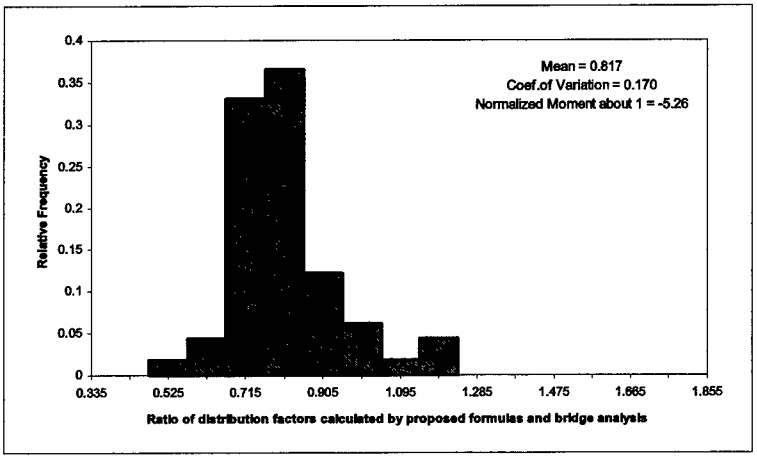


c. Non-LRDF formula

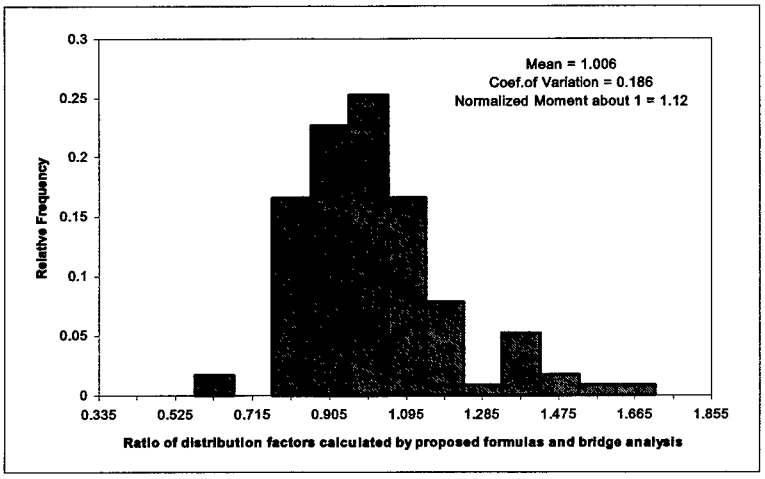
Figure 92. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, prestressed girder, bending moment in interior girders for single lane



a. New formula

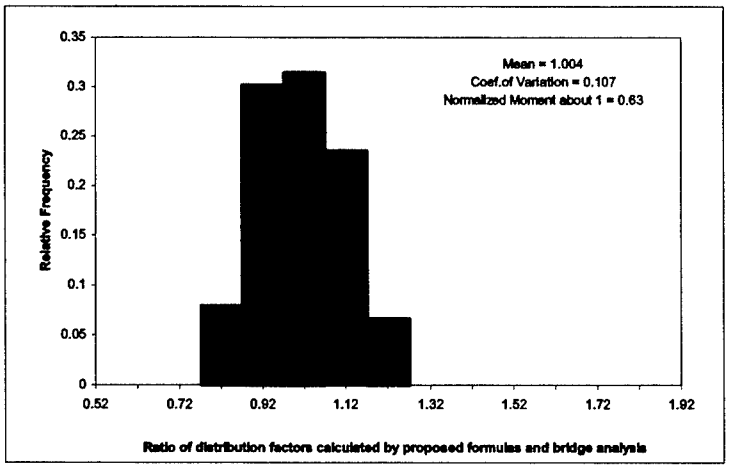


b. LRFD formula

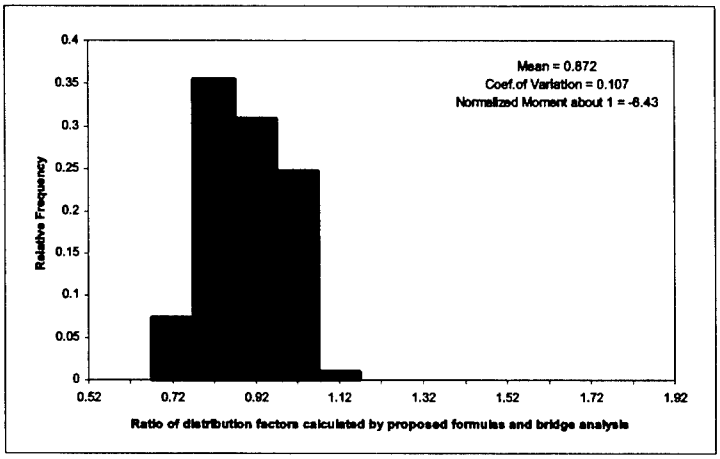


c. Non-LRDF formula

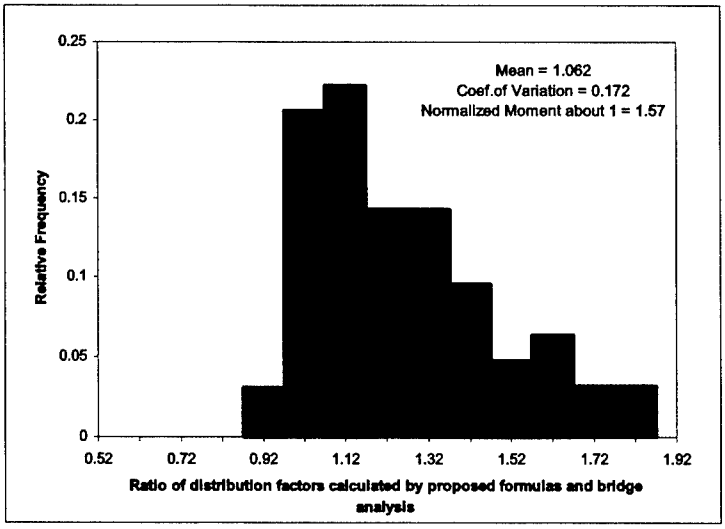
Figure 93. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for PLS and HEMMT vehicles, concrete T-beam, bending moment in interior girders for single lane



a. New formula

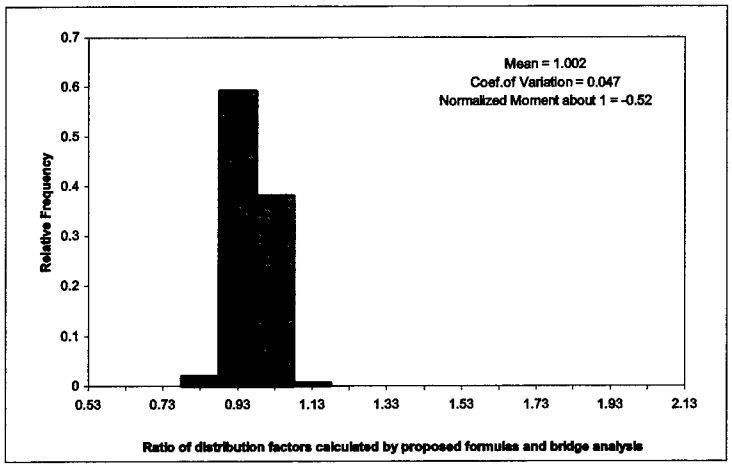


b. LRFD formula

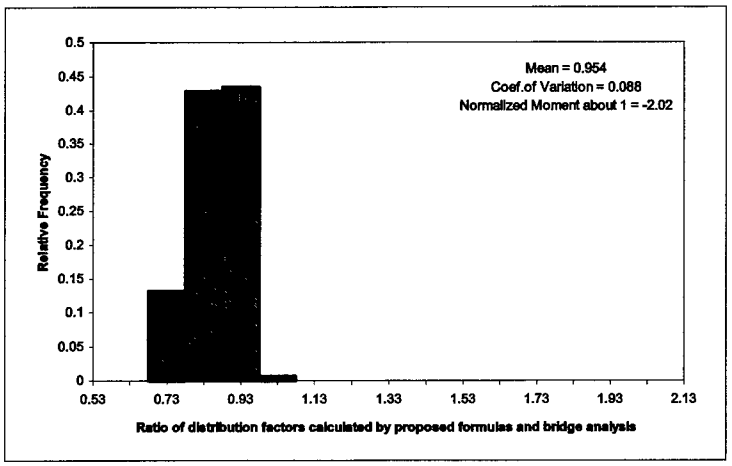


c. Non-LRDF formula

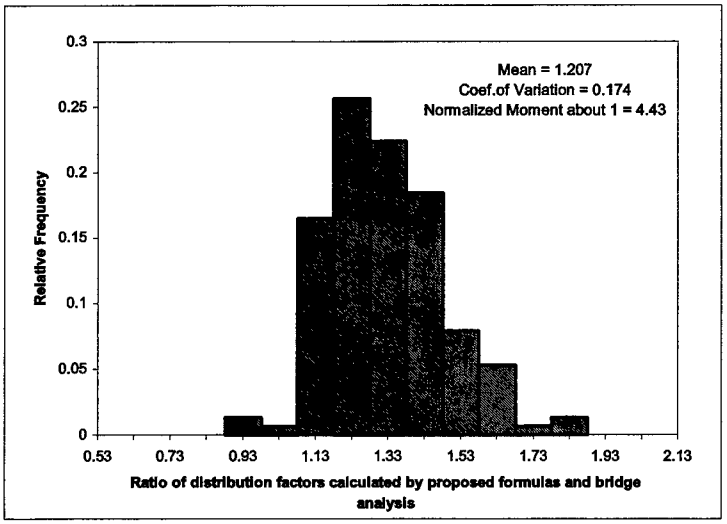
Figure 94. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicles, all beam bridges, bending moment in interior girders for single lane



a. New formula

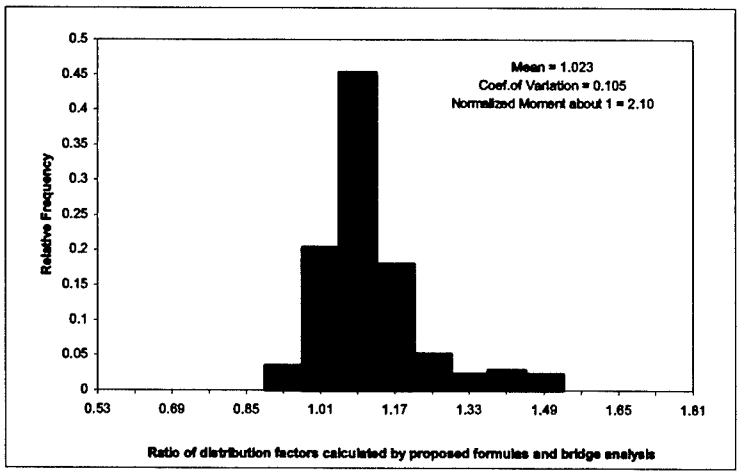


b. LRFD formula

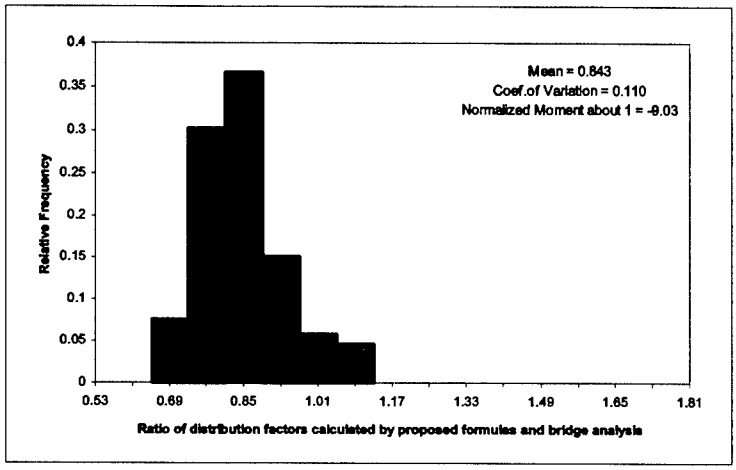


c. Non-LRDF formula

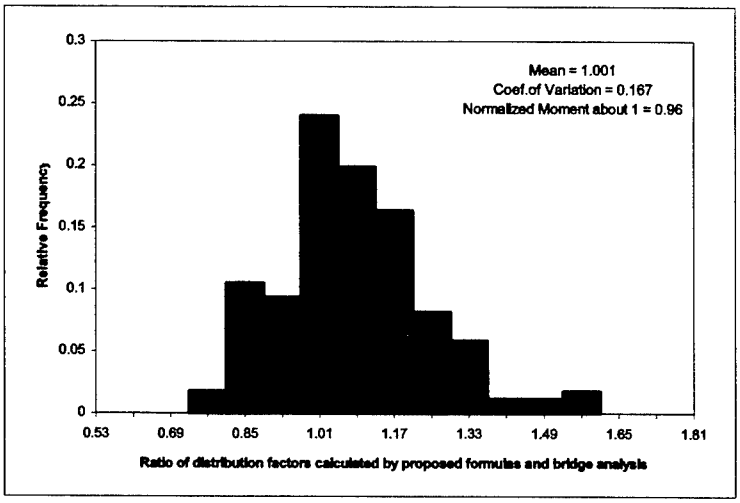
Figure 95. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicles, steel girder, bending moment in interior girders for single lane



a. New formula

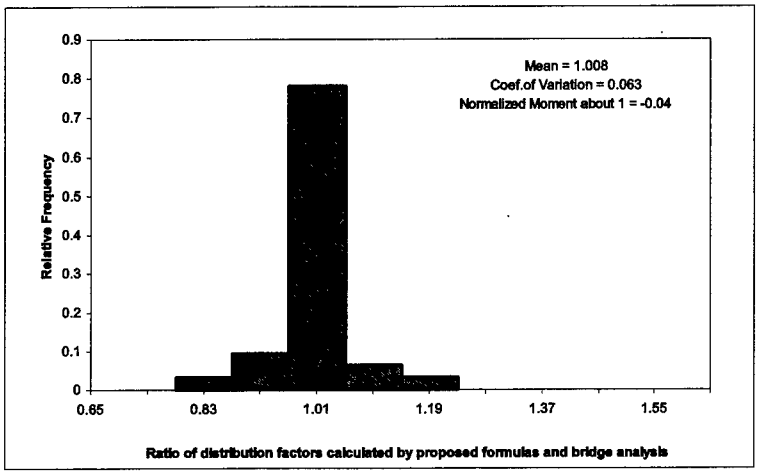


b. LRFD formula

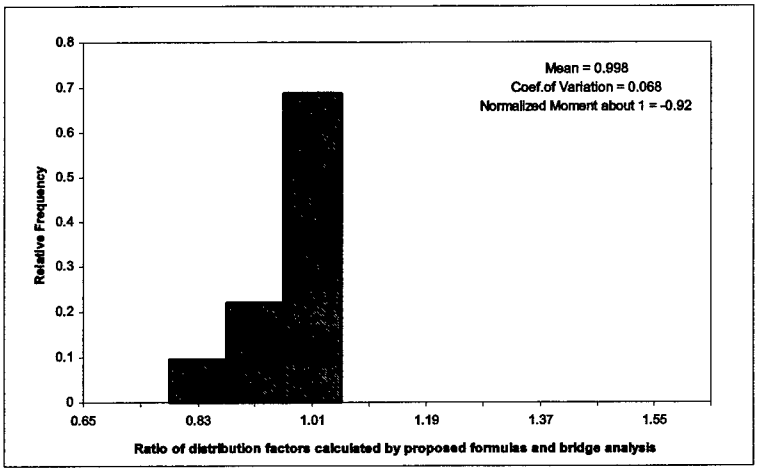


c. Non-LRDF formula

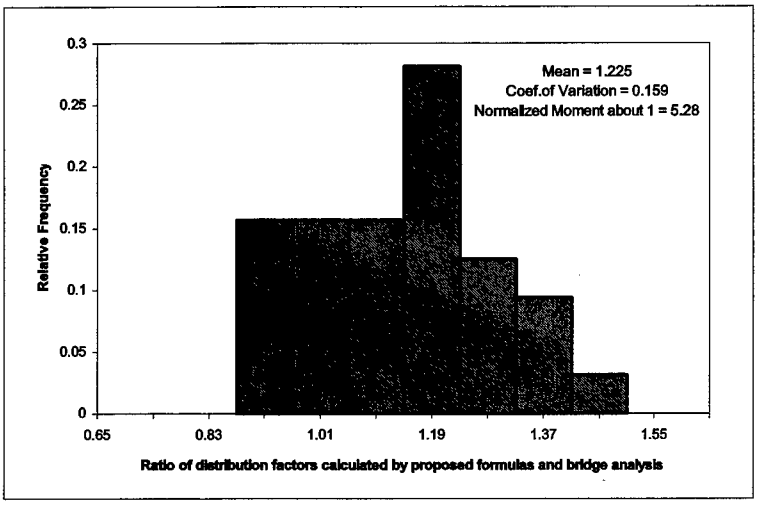
Figure 96. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicle, prestressed girder, bending moment in interior girders for single lane



a. New formula

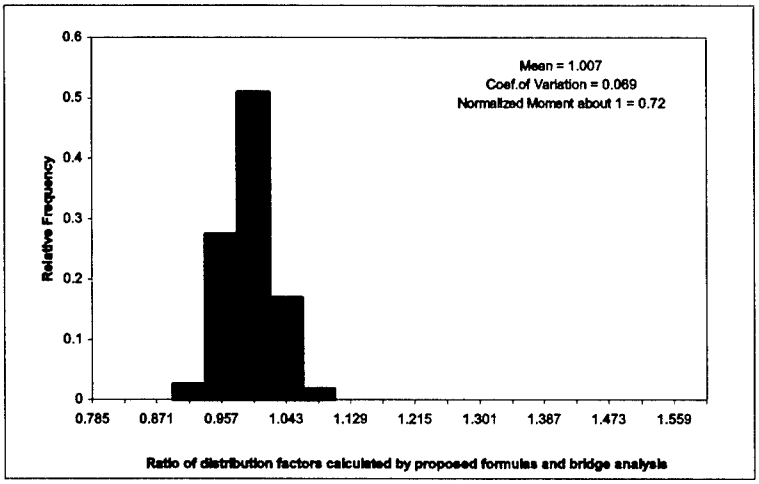


b. LRFD formula

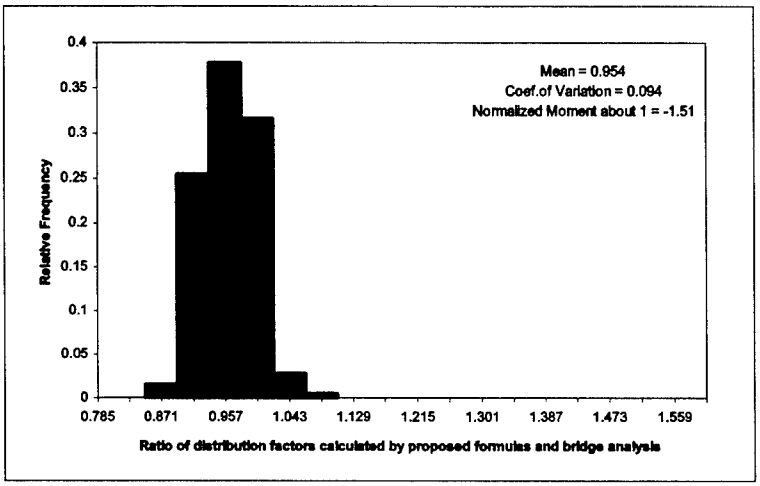


c. Non-LRDF formula

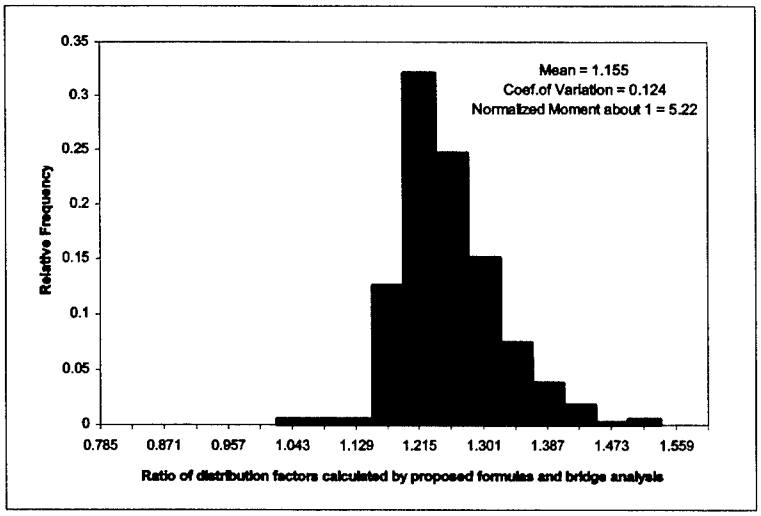
Figure 97. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for HETS vehicle, concrete T-beam, bending moment in interior girders for single lane



a. New formula

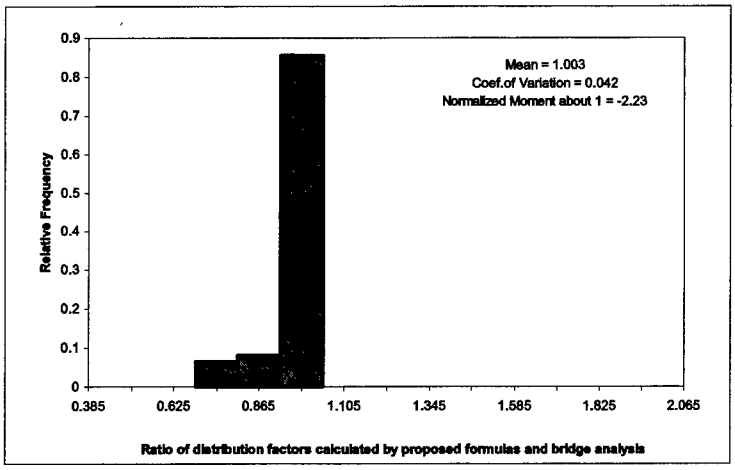


b. LRFD formula

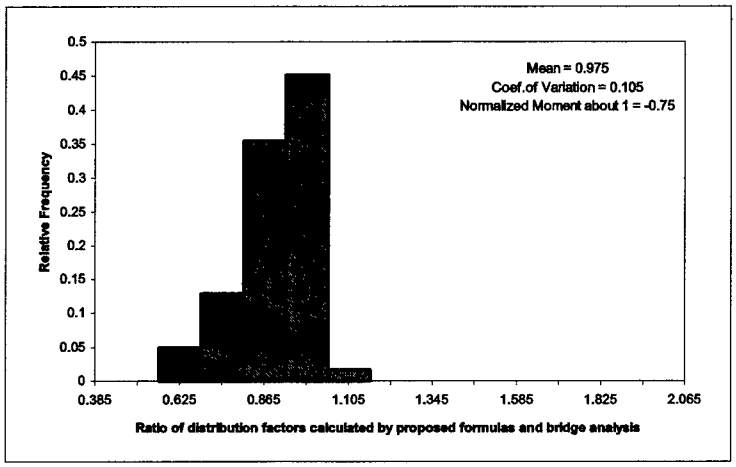


c. Non-LRDF formula

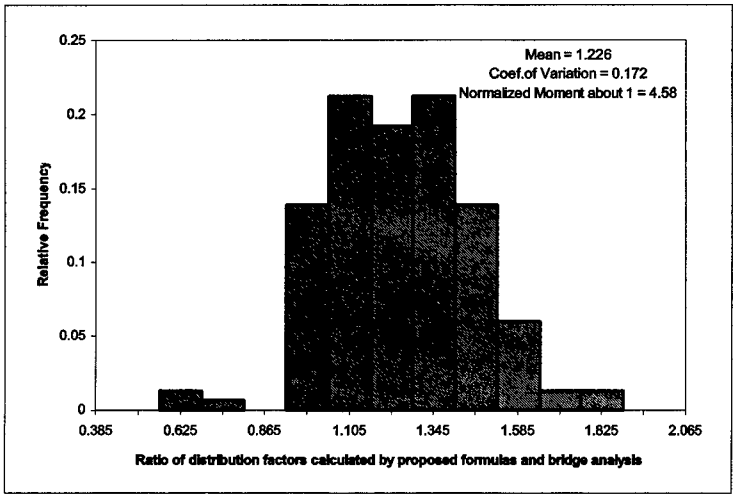
Figure 98. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, all beam bridges, bending moment in interior girders for single lane



a. New formula

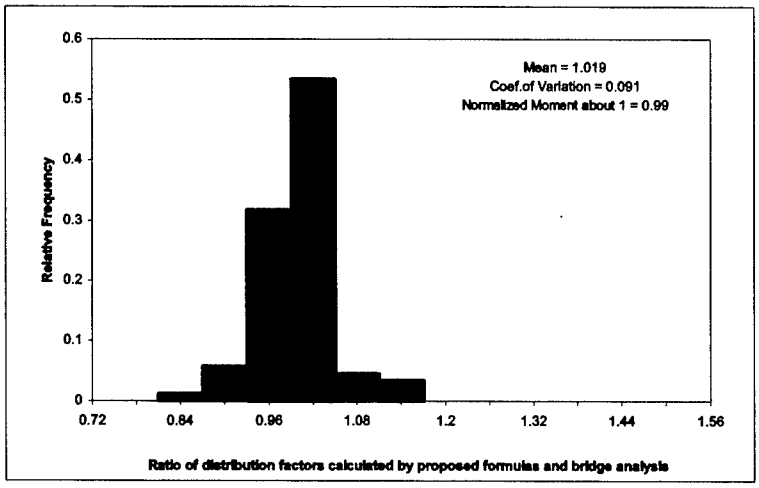


b. LRFD formula

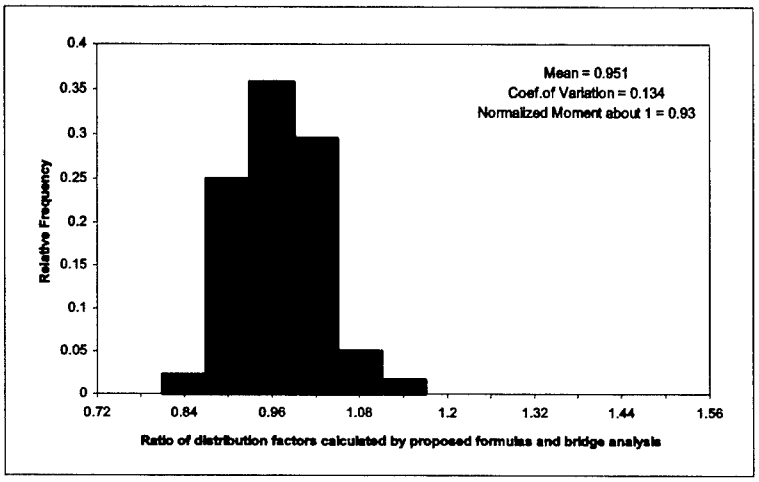


c. Non-LRDF formula

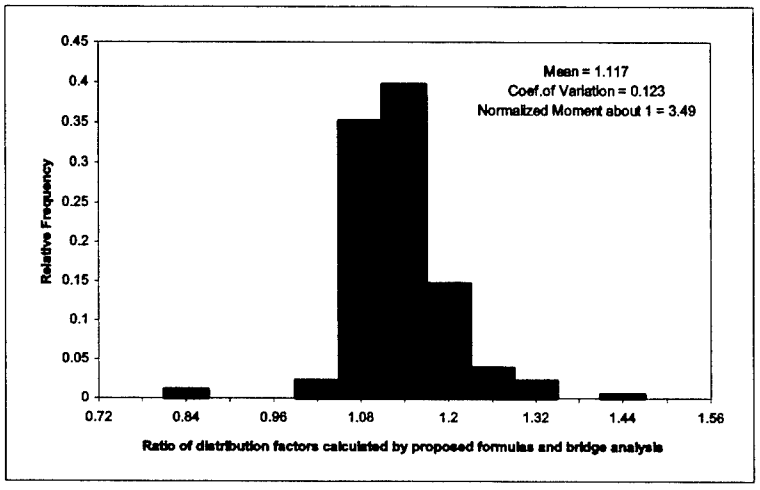
Figure 99. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, steel girder, bending moment in interior girders for single lane



a. New formula

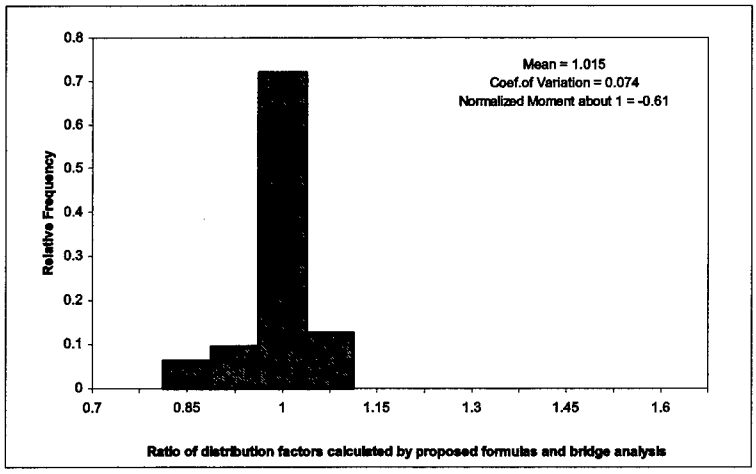


b. LRFD formula

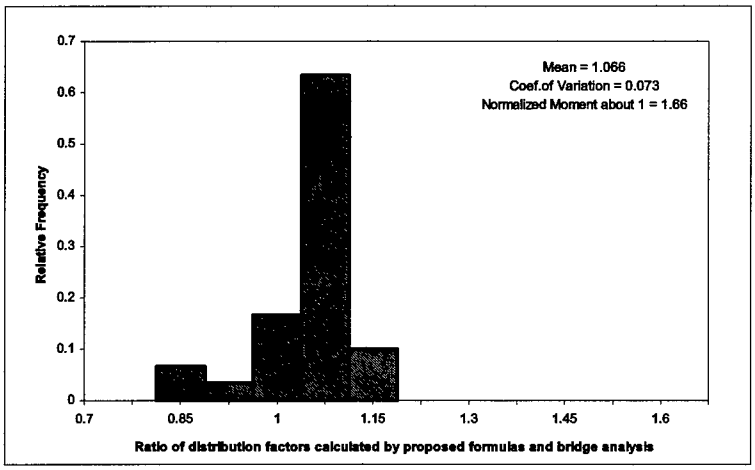


c. Non-LRDF formula

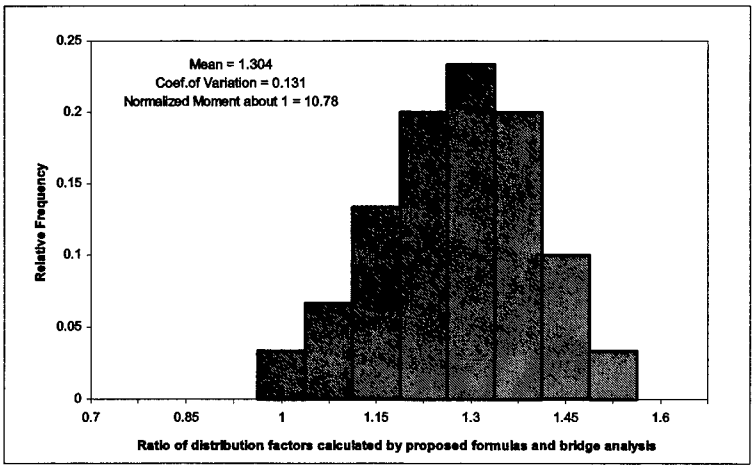
Figure 100. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, prestressed girder, bending moment in interior girders for single lane



a. New formula

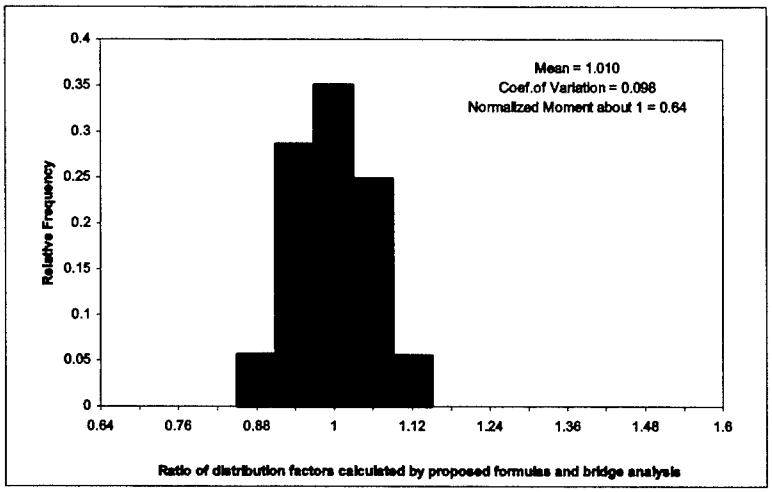


b. LRFD formula

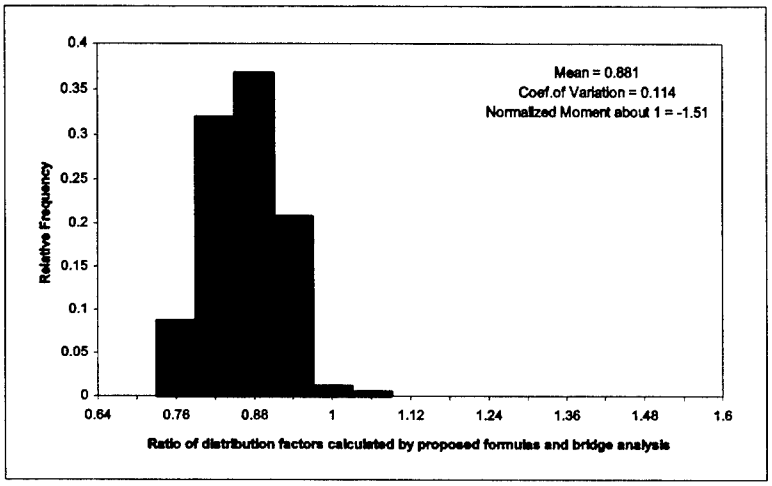


c. Non-LRDF formula

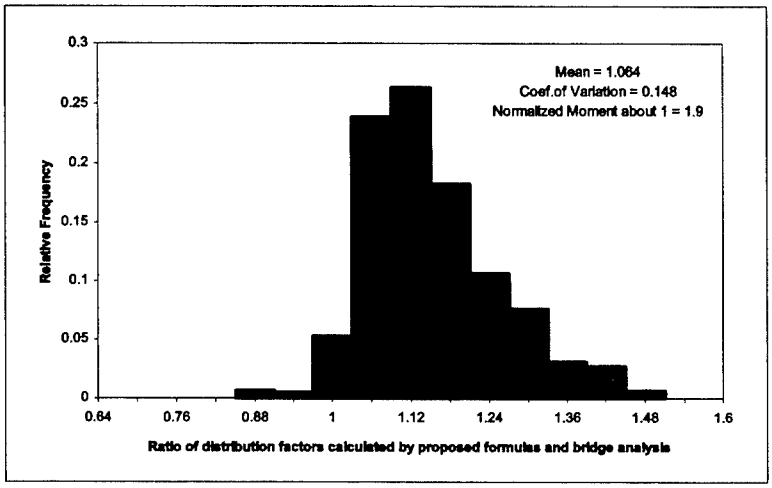
Figure 101. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for Abrams vehicle, concrete T-beam, bending moment in interior girders for single lane



a. New formula

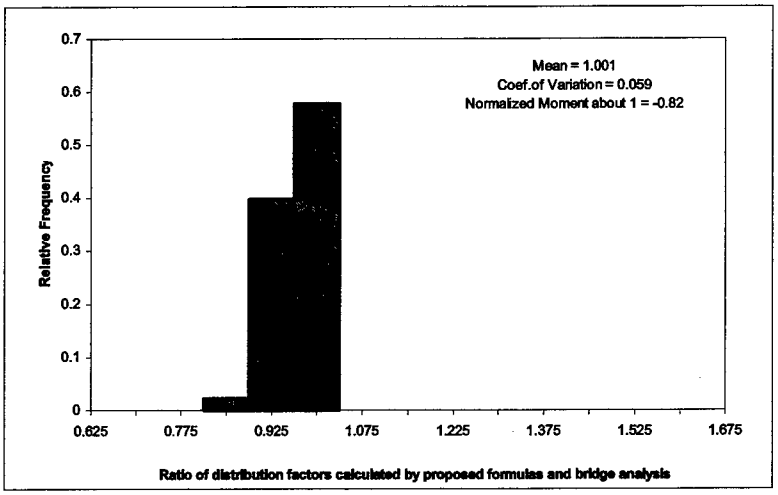


b. LRFD formula

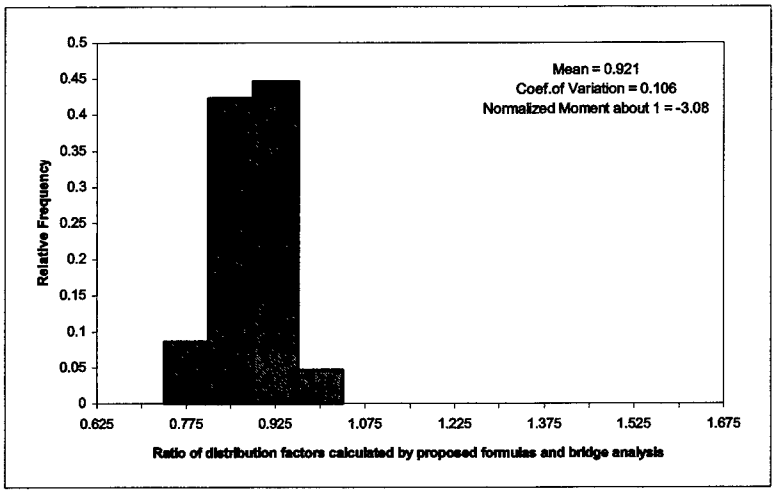


c. Non-LRDF formula

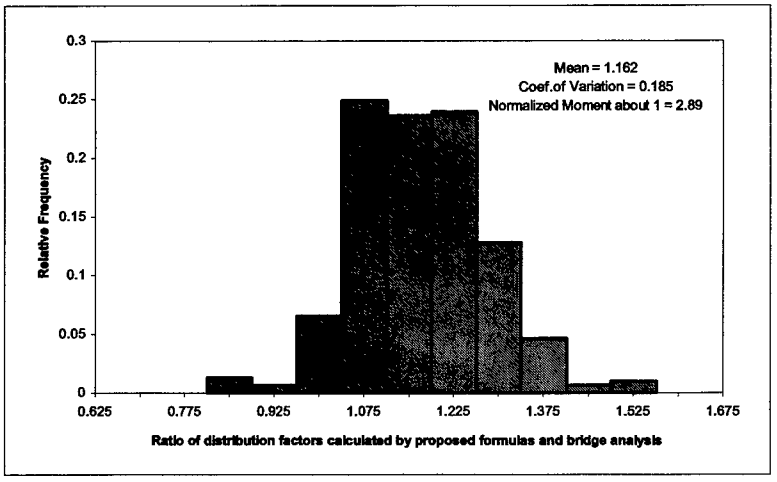
Figure 102. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, all beam bridges, bending moment in interior girders for single lane



a. New formula

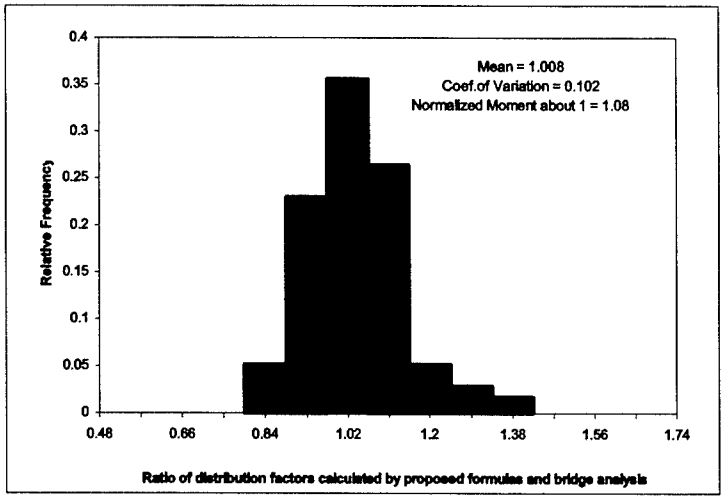


b. LRFD formula

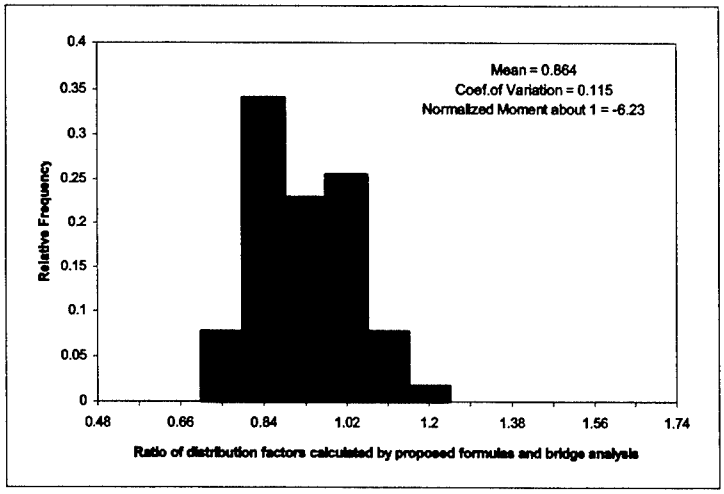


c. Non-LRDF formula

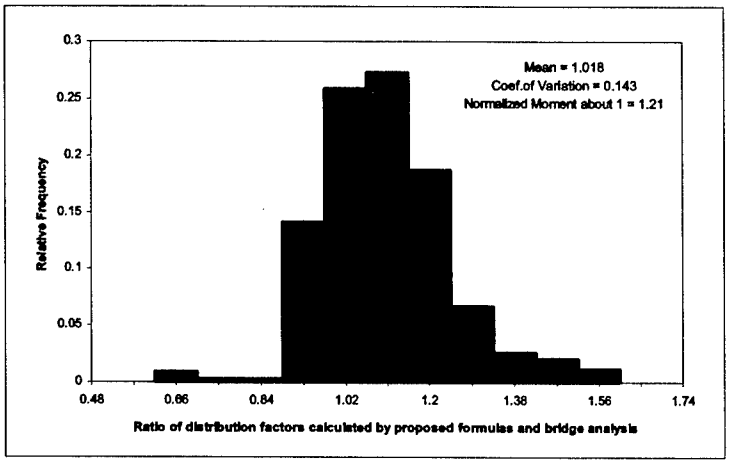
Figure 103. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, steel girder, bending moment in interior girders for single lane



a. New formula

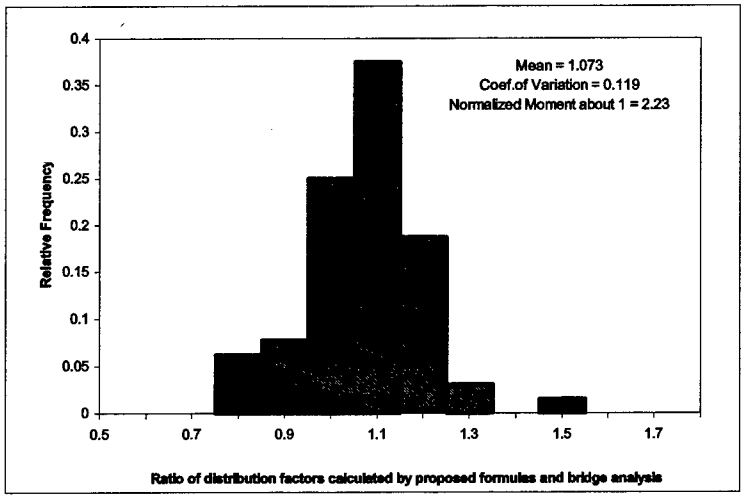


b. LRFD formula

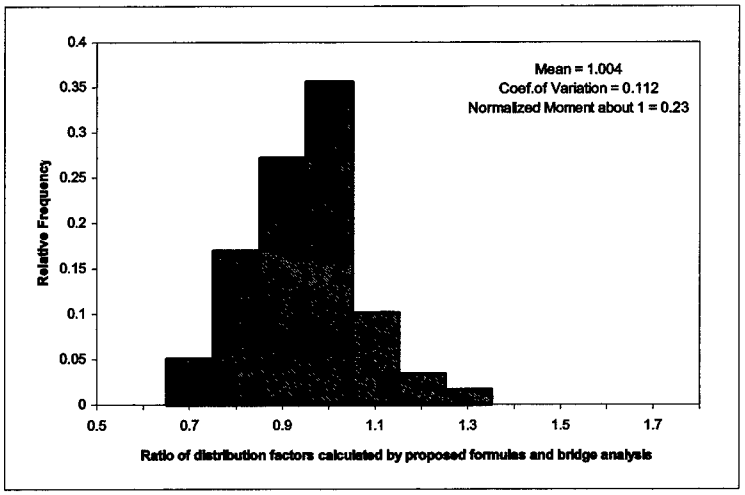


c. Non-LRDF formula

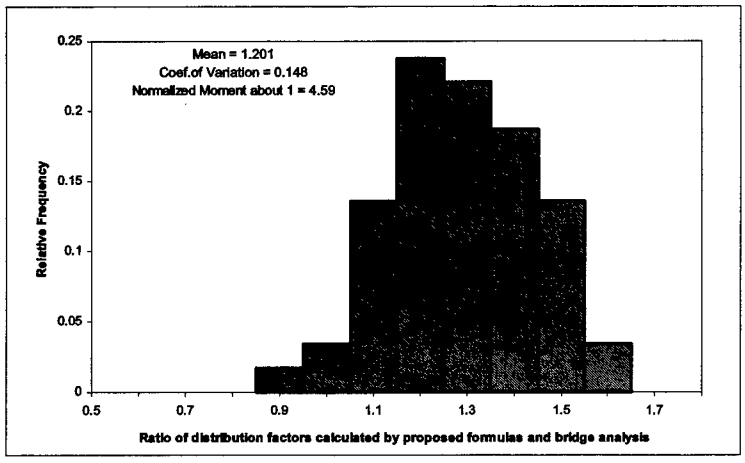
Figure 104. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, prestressed girder, bending moment in interior girders for single lane



a. New formula

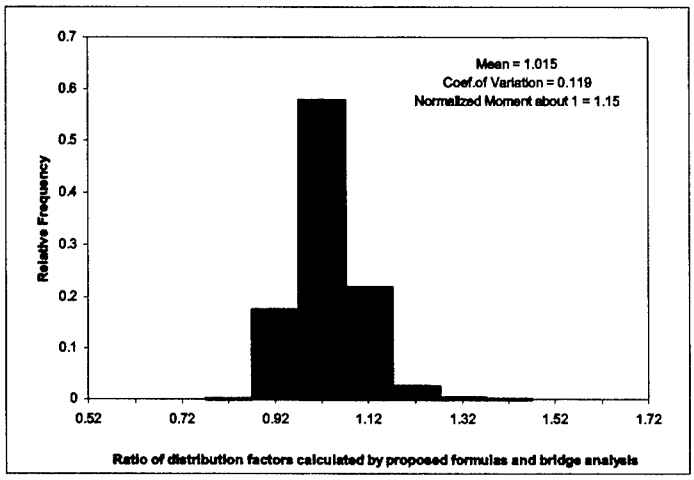


b. LRFD formula

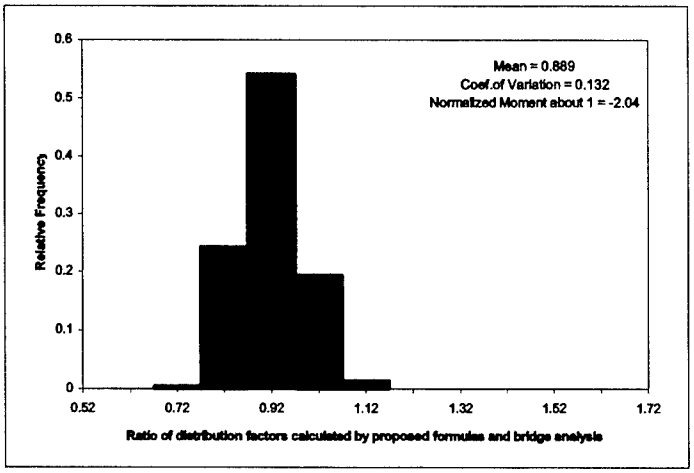


c. Non-LRDF formula

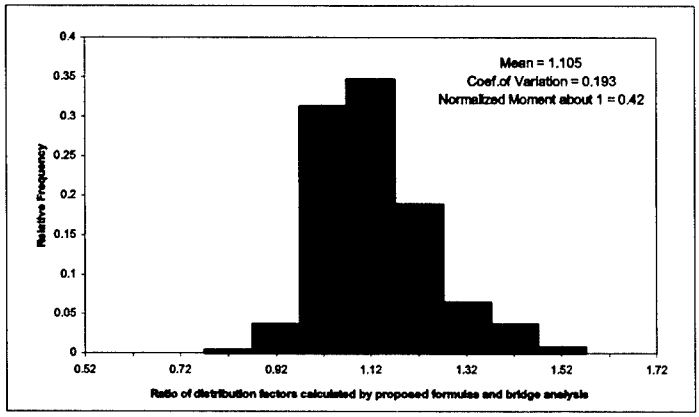
Figure 105. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for M113 and Bradley vehicles, concrete T-beam, bending moment in interior girders for single lane



a. New formula

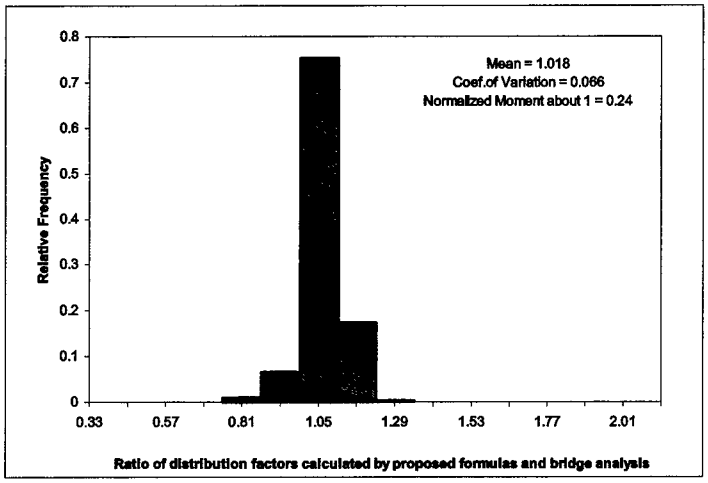


b. LRFD formula

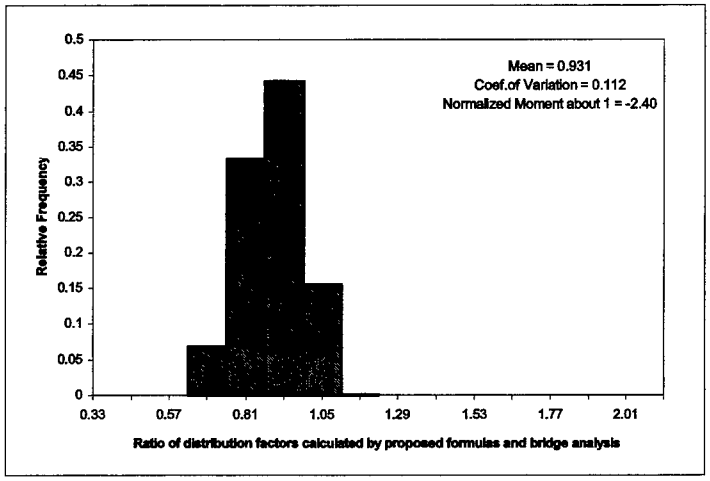


c. Non-LRDF formula

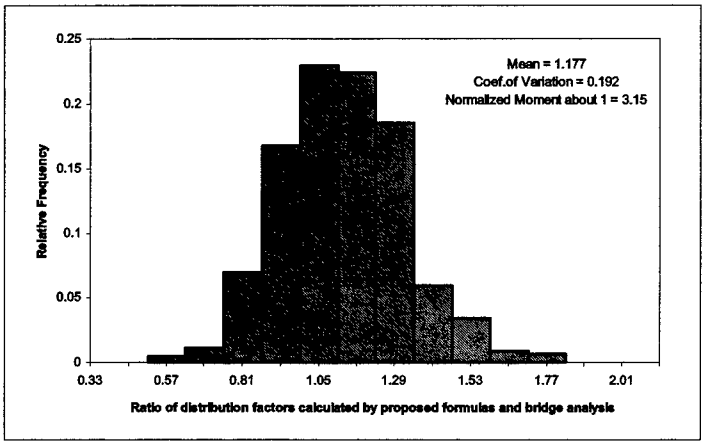
Figure 106. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for All vehicles, all beam bridges, bending moment in interior girders for single lane



a. New formula

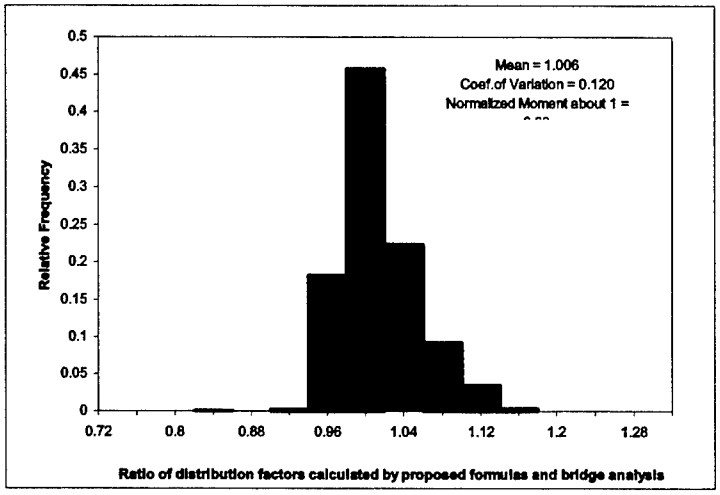


b. LRFD formula

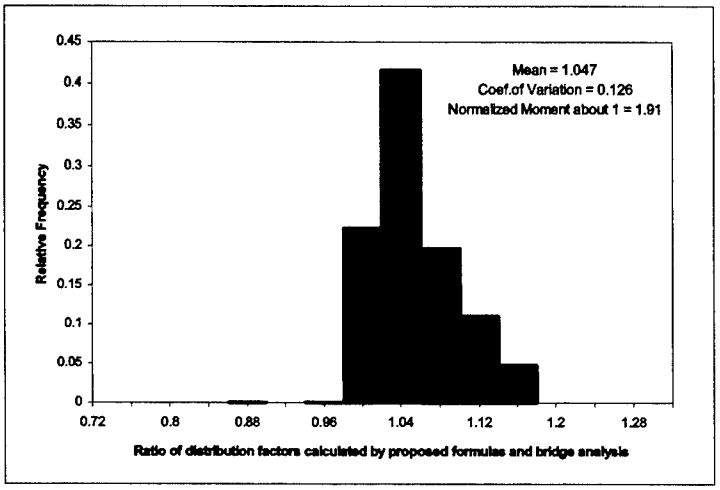


c. Non-LRDF formula

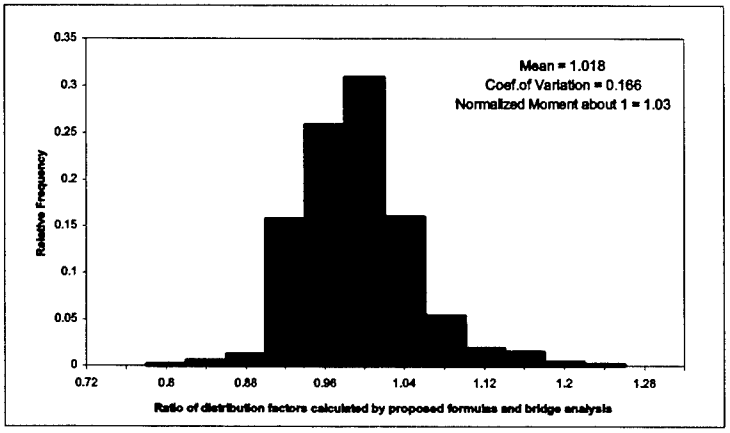
Figure 107. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for All vehicles, steel girder, bending moment in interior girders for single lane



a. New formula

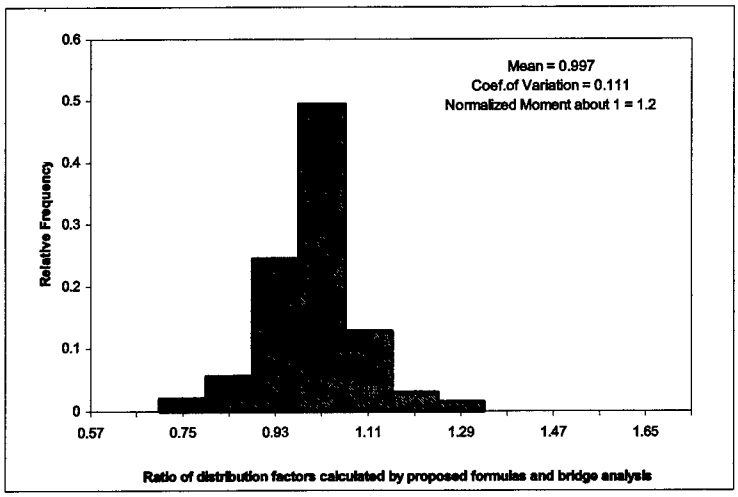


b. LRFD formula

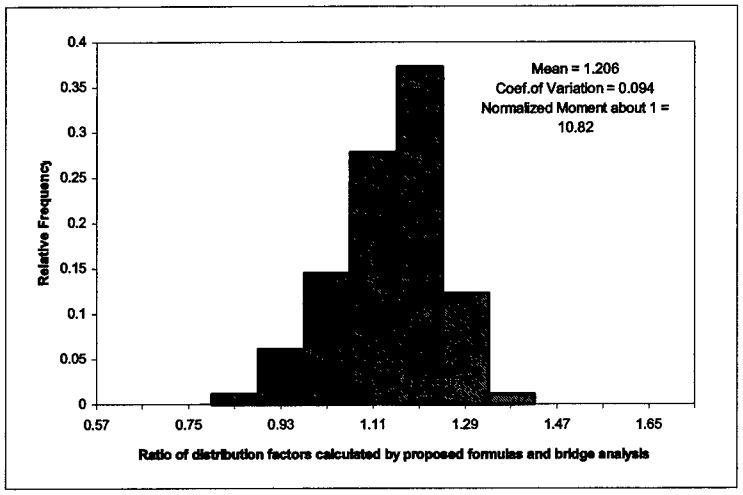


c. Non-LRDF formula

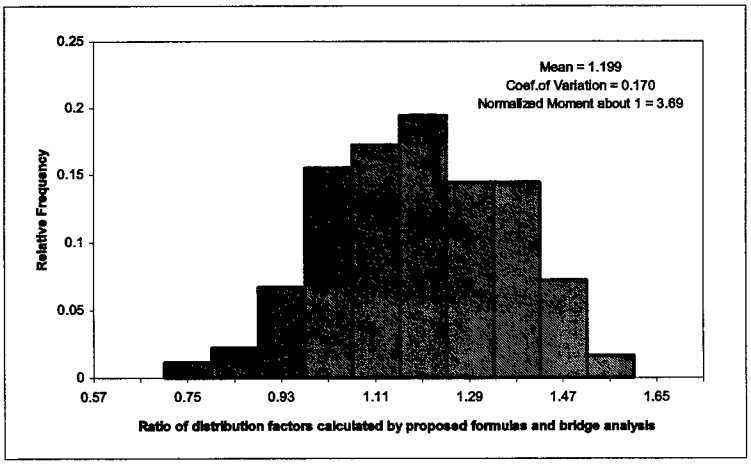
Figure 108. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for All vehicles, prestressed girder, bending moment in interior girders for single lane



a. New formula



b. LRFD formula



c. Non-LRDF formula

Figure 109. Comparison of distribution factor ratios calculated by the proposed formulas, LRFD formulas, and non-LRFD formulas for All vehicles, concrete T-beam, bending moment in interior girders for single lane

12 Conclusions

This report describes the development and validation of formulae to predict lateral load distribution factors specifically for key military vehicles. These formulae should offer a vast improvement in capabilities for load rating of bridges for military usage. The distribution factors currently used by the military are often too inaccurate and result in overly restricted bridge usage or, worse, usage of bridges that are unsafe.

The comparisons of these new formulae with detailed analytical data indicate that they are, in fact, considerably more accurate than those currently in use. However, before these formulae are adopted by the military as doctrine, additional validation should be accomplished using onsite load testing. More statistical work may also be necessary to ensure that the formulae are on the conservative side a high percentage of the time; i.e., the "reliability" of the formulae should be better understood.

References

AASHTO. (1994). "Guide specification for distribution of loads for highway bridges," Washington, DC.

AASHTO. (1996). "Standard specifications for highway bridges", 16th ed., Washington, DC.

Bakht, B., and Jaeger, L. G. (1985). *Bridge analysis simplified.* McGraw Hill New York, NY.

Bakht, B., and Jaeger, L. G. (1989). *Bridge analysis by microcomputer.* McGraw Hill, New York, NY.

Douglas, J. (1969). *An introduction to dimensional analysis for engineers.* Pitman Publishing Corp.

Minor, J., and Woodward, C. (2001). "Bridge analysis study, phase II & phase III," (Report in prepared for the U.S. Army Waterways Experiment Station, New Mexico State University.

SAS Institute Inc. (1989). *SAS/STAT user's guide*, Version 6, 4th ed., Vol 3, Cary, NC.

Singh, M. P., Thangjithan, S., and Singh, S. (1998). "Parametric sensitivity analysis of multi-girder bridge systems," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Zokai, T., Osterkemp, T.A., and Imbsen, R.A. (1991). "Distribution of wheel loads on highway bridges," NCHRP Final Reports, Vol 1, and 2, 12-26(1).

Zokai, T., Mish, K. D., and Imbsen, R.A. (1993). "Distribution of wheel loads on highway bridges, phase III," NCHRP Final Report, 12-26(2).

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
July 2002	Final report	

4. TITLE AND SUBTITLE

Lateral Load Distribution Factors for Military Vehicles on Multi-Girder Bridges

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Juan C. Pinero, Mahendra P. Singh, James C. Ray

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University, Blacksburg, VA 24061;

U.S. Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/GSL TR-02-11

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

In general, military vehicles are heavier, wider, and have much different axle/tire configurations than "civilian" type trucks for which conventional load distribution factors have been developed. Thus, use of conventional load distribution factors to rate bridges for military deployments often results in inaccurate ratings and thus unnecessarily limits mobility options for the military or threatens the safety of military personnel. This report provides an overview of an extensive study conducted to develop lateral load distribution factors specifically for military vehicles.

The study considered six different types of military vehicles, three of which were wheeled vehicles and the other three were tracked vehicles. Formulas were developed for three different types of bridges: steel girder bridges, prestressed concrete bridges, and concrete T-beam bridges.

The study resulted in a total of 52 new formulas for different categories of military vehicles, different types of bridges, bending moment and shear force values, interior and exterior girders, and for single- and multiple-lane loading cases. The distribution factors calculated with the formulas were compared with those calculated by direct analyses of the bridges to evaluate the accuracy of the proposed formulas.

15. SUBJECT TERMS

Bridge; Load distribution; Military vehicle loading; Bridge loading; Load distribution equations

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		144	